

Article

A Digital Decision-Support Framework for Risk Identification and Mitigation Management in Environmental Impact Assessment

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Abstract

Environmental Impact Assessment (EIA) plays a critical role in ensuring sustainable development by identifying and mitigating the adverse effects of major construction projects. However, current EIA practices, especially in developing countries, often lack a systematic approach to identifying risks and evaluating and selecting mitigation strategies, leading to suboptimal environmental protection. This is coupled with a lack of data, inconsistencies in the quality of reports, and a low compliance rate with environmental management plans, which characterize mega infrastructure projects. In this regard, the research aims to develop a structured digital framework for identifying, assessing, and prioritizing mitigation strategies in EIAs for large-scale construction projects. The research method combines a review of the existing literature and case studies of past EIAs to gather insights into common mitigation measures and their effectiveness. Based on this, key environmental impacts are analyzed and potential mitigation strategies are categorized. A multi-criteria decision analysis (MCDA) framework is proposed to evaluate mitigation strategies using the Analytical Hierarchy Process (AHP) to rank and select optimal mitigation approaches. Eventually, the research develops an EIA Risk and Mitigation Management framework (EIA-RMMS), which is a digital system developed to facilitate EIA implementation, indicating standardized risk types and potential mitigation measures. The EIA-RMMS links to project management and enables integration with Artificial Intelligence and Machine Learning. The proposed framework is applied to three case study metro line projects in Egypt to prove its effectiveness in data analysis, decision-support and report structuring. The findings are valuable for EIA practitioners and project developers seeking to align infrastructure development with ecological and social sustainability goals.

Keywords: environmental impact assessment; mitigation; multi-criteria decision analysis; environmental risks; infrastructure projects

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1. Introduction

Environmental Impact Assessment (EIA) refers to an early warning process for expected development impacts and acts as a preventive and mitigating tool to adjust

impacts to acceptable levels through internationally accepted requirements and standards of practice [1–3]. It is concerned with environmental protection to enable efficient management of natural resources based on integrity, utility and sustainability [4–6]. Thus, the use of EIA in mega construction projects is a must to reduce the expected short and long-term environmental impacts [7,8].

Mega construction projects such as large-scale transportation networks are associated with a broad range of environmental risks arising from their construction scale, spatial footprint, and long operational lifespans. Key risks include extensive land take and habitat fragmentation during site preparation and project development; deterioration in air quality and increased greenhouse gas emissions during construction and operation; soil degradation and contamination resulting from excavation, material storage, and waste handling; and alterations to surface and groundwater systems caused by earthworks, drainage modification, and runoff pollution [9]. Addressing these risks requires a comprehensive mitigation strategy implemented across all project phases. Effective mitigation measures include careful site and alignment selection to avoid environmentally sensitive areas [7,10], informed material selection to reduce embodied carbon and pollutant release [11,12], and the adoption of sustainable design and construction practices that limit emissions, noise, vibration, and waste generation. These strategies should be supported by robust management practices, including environmental monitoring, adaptive construction management, and compliance control, as well as by post-construction restoration and rehabilitation planning [13,14] to reinstate ecological functions and minimize long-term impacts on air, water, and soil systems [15].

In recent decades, Egypt has seen rapid urban growth, which has driven heavy investment in infrastructure projects, especially transportation, to help reduce traffic congestion, and improve mobility [16]. Despite these benefits, these types of projects always have long-term and short-term impacts on environmental and social levels [17,18]. Therefore, it is a must to complete and submit an EIA report from the EEAA to proceed with construction [19]. Nevertheless, the practice of EIA frequently encounters a decoupling between theory and practice, especially in developing countries, as in the case of Egypt [9,20]. This gap results in environmental reports that are qualitative, static, and disconnected from the actual construction and operational phases [21]. The law that rules the Egyptian EIA system is Law 4/1994 (amended by Law 9/2009) and it is managed by the Egyptian Environmental Affairs Agency (EEAA) [19]. Based on the severity of environmental impact, projects are classified to white, grey and blacklists. In this regard, it is noted that the National Authority for Tunnels (NAT), which is responsible for transportation networks [22], and the EEAA [19] do not have a single digital platform to monitor the live implementation of environmental commitments of such projects, and therefore there is a disparity in compliance monitoring.

Using advanced management and digitalization tools can serve as a transformative solution to these challenges by converting unstructured qualitative assessments into structured, actionable data [23]. This can standardize risk identification and ensure that mitigation measures are consistent with international best practice [21]. Further, it can automate environmental assessment calculations and provide predictive insights that allow transitioning from administrative reporting to proactive risk management [15,24].

Thus, the primary aim of this research is to develop an EIA Risk and Mitigation Management framework (EIA-RMMS), a digital system to streamline EIA implementation. The proposed EIA-RMM framework operates primarily as a rule-based decision-support system. Core functionalities—including risk–mitigation matching, priority assignment, and cost aggregation—are governed by explicit conditional logic and multi-criteria decision analysis (MCDA)/Analytical Hierarchy Process (AHP) formulations derived from expert judgment and established assessment criteria. Artificial Intelligence (AI) is employed

in a supportive role for data structuring, automation, and summarization, rather than as a self-learning decision agent. As such, the system's behavior is transparent, reproducible, and auditable, ensuring suitability for regulatory and professional EIA applications. This strategy can help make EIA a better practical, environmental impact management and empirical decision-support tool and sustain the critical nature of human judgment in the environmental assessment and regulatory decision-making processes [25]. Its contribution is strongly oriented toward procedural, managerial, and monitoring aspects. The present work performs the following:

- Structures concepts (risks, receptors, mitigation, and lifecycle phases);
- Defines decision logic and workflows;
- Integrates tools (MCDA/AHP, rule-based logic, and AI-assisted automation);
- Supports decisions across different project phases, i.e., planning, design, construction and operation.

2. Literature Review

This section reviews the existing literature concerning EIA, its definition, benefits and challenges. It scrutinizes the EIA legal and institutional framework in Egypt to pinpoint existing challenges. Finally, it discusses the use of digital technologies to resolve some of these existing challenges.

2.1. Principles of EIA

EIA was first introduced as a non-mandatory framework in the National Environmental Policy Act in 1969, and then it was enforced as a law in 1970 for mega construction projects [26]. It is widely recognized as part of the international policy that integrates environmental concerns in the process of urban development, planning and decision-making [25]. Transnational instruments such as the Espoo Convention on EIA attempts to standardize the process across member states [27]. The EIA process is divided into three stages: Plan, Do and Act. The former includes screening, scoping and planning an EIA report. The screening step determines the type of projects that require an EIA process and identifies the type of environmental assessment. The scoping step defines the environmental risks and determines the following steps to be undertaken in an organized framework. The preliminary assessment provides the required background data needed for identifying and assessing risks and their corresponding mitigation measures. The Do stage includes conducting the analysis and preparing the EIA report. This is followed by reviewing and seeking public participation and consultation. The Act stage ends the process by evaluating mitigation measures, making decisions, and establishing a mechanism for monitoring and feedback [28,29].

Benefits of an EIA include providing a methodical assessment tool, estimating the benefit/cost trade-off of alternative actions, enabling public review and participation. This, in turn, constitutes an effective mechanism for coordination, integration, negotiations and feedback to achieve a balance between the impact of a development process and its associated environmental concerns [21,30].

There are some limitations to the implementation of the EIA method which make it complicated and time-consuming [8,31]. These are attributed to using predictive methods which are not always supported by scientific information [21,32]. Process-associated limitations occur due to the limited range of possible alternatives, lack of strategies for preventing environmental intervention, lack of follow-up actions and insufficient refinement of the selection criteria [33,34]. Another type of limitation is associated with data insufficiency and limited reliability, as well as the lack of availability of manpower and financial resources to consider the interdisciplinary character of this level of analysis [35,36]. This

can be mitigated using a comprehensive framework of environmental assessment, providing a wider platform of environmental data gathering, analysis and decision-support relating to higher levels of strategic thinking [37,38].

2.2. Digital Tools for Decision-Making and Environmental Assessment

Advanced technologies are changing the building and construction industry, offering process optimization, minimizing errors, shortening implementation time, and enhancing accuracy and reliability [39,40]. Environmental management is being developed through AI and digital tools to enhance environmental surveillance, prediction of impacts, and decision-making based on data-driven analysis [41]. In practice, such systems may be based on the automated processing of large environmental datasets, the identification of patterns and irregularities, and assistance in the accelerated interpretation of the environmental situation, which may be more consistent than raw manual reporting [41].

Building Information Modelling (BIM) integration is recommended as an instrument to enhance the integration between the EIA process and project development phases [21]. Digital tools enable the creation of organized databases and analysis engines that can facilitate better systematization of risks and mitigation strategies and develop monitoring indicators, which enhances comparative analysis and increases transparency [21]. In this regard, digital-based EIA can be most valuable at three critical stages: scoping (automating initial risk identification), quality assurance (checking proposed mitigations against legal standards), and compliance monitoring (transforming static reports into live, trackable dashboards for regulators) [15,37].

Recent studies concerning MCDM highlight the growing need for transparent and robust decision-support frameworks capable of resolving trade-offs among conflicting sustainability objectives, particularly in infrastructure and energy planning contexts [13,42]. In this regard, prior work demonstrates the value of combining expert judgment with structured MCDA techniques to enhance transparency and consistency in complex decision-making processes [43].

This intelligence fuels accurate forecasts, predicts potential delays, recommends alternative strategies and supports the decision-making process. Also, it can be a powerful planning tool providing realistic timelines and suggesting efficient optimization, communication, and documentation strategies. Such methods are consistent with the necessity of enhancing EIA practice in developing countries, where EIA is prone to fractured information and poorly developed follow-up measures [8,21]. Digital practices may also facilitate the connection between impacts predicted and mitigation plans and facilitate the display of outputs in a format that would be easier to monitor across sectors and project stages [21].

This literature review shows that although traditional EIA methodologies continue to be restrictive due to fixed reporting, disjointed risk-reduction connections, and ineffective post hoc follow-up, digital and AI-based solutions have robust potential to solve these limitations [8,21]. Nevertheless, regardless of this increasing potential, the literature indicates that digital and AI tools are usually implemented in independent or incomplete forms, and there is no overall framework that integrates environmental risk detection, mitigation efficiency, and monitoring across the project sectors and different lifecycle stages [21]. Also, the accountability, transparency, and responsibility are also of concern when it comes to the utilization of AI in environmental decision-support [40]. This justifies the trend towards interpretable, rule-based, and well-documented digital systems in EIA-related tasks that require justification of decisions to be made [44].

Addressing these limitations requires the development of integrated digital decision-support frameworks that combine structured risk-mitigation management, transparent decision logic, and adaptive monitoring capabilities. Such frameworks can strengthen the

operational relevance of EIA by transforming environmental assessment outputs into actionable management tools, thereby improving accountability, implementation consistency, and long-term environmental performance in infrastructure projects.

3. Materials and Methods

The research method includes the following steps:

- Data collection and case study application; individually for each of the three case studies, then comparatively for the three projects.
- Developing the proposed framework.

3.1. Data Collection and Case Study Analysis

This study applied a qualitative comparative analysis for three EIA case studies in Egypt: Cairo Metro Line 3 Phase 3 [45], Cairo Metro Line 4 Phase 1 [22], and the 10th of Ramadan Light Rail Transit (LRT) Project, as shown in Figure 1 [46]. These projects were selected based on common project type (metro lines), geographical location (Egypt), legislative constraints (EEAA), scale (mega construction projects), and full availability of EIA reports obtained from the official EEAA website [19]. Cairo Metro Line 3 Phase 3 connects Attaba and Rod El Farag, passing through 15 stations along 17.7 km. This project is co-financed by NAT, the French Development Agency, and the European Bank for Reconstruction and Development [45]. Cairo Metro Line 4 Phase 1 connects the El Malek El Saleh and 6th October City borders (≈15 km, 15 stations). The EIA report was prepared by the NAT under Japan International Cooperation Agency supervision and the Japan bank of international cooperation, with the approval of the EEAA in Egypt [22]. The 10th of Ramadan LRT Project links Cairo, the New Administrative Capital, and the 10th of Ramadan City; it has 19 stations and is 103 km long. The project is implemented by the NAT and supervised by the Ministry of Transport [46].

Based on the official EIA reports for each case study project, the environmental/social receptors are identified and classified for each project phase (pre-construction, construction and operation) into major, moderate, minor, negligible and positive impacts to study how environmental management evolves over the project lifetime. Then their corresponding mitigation measures are identified, described, and classified, and the parties responsible for implementing these measures and the monitoring and follow-up procedures are stated. For case studies 1, 2 and 3, these details are elaborated in Appendix A.1–A.3, respectively. The next step compares the three case studies and their impact significance before and after applying the defined mitigation measures (refer to Appendix A.4).

For the purpose of this study, 100 mitigation measures across the three projects are classified and coded (M1:M100) based on the project lifecycle and receptors, as shown in Appendix A.5. The coding exercise enables cross-project comparison of mitigation coverage, revealing both areas of convergence—where similar mitigation strategies recur—and areas where certain risk categories remain under-specified or unevenly treated. It should be noted that the ‘before versus after mitigation significance reduction’ is derived from EIA report claims and author interpretation, rather than observed monitoring data on environmental outcomes or compliance. To enhance methodological rigor and reduce subjectivity in dataset construction, the coding of environmental and social risks and mitigation measures was conducted by multiple coders with expertise in EIA and infrastructure projects. Each coder independently reviewed the EIA reports and assigned receptors, lifecycle phases, severity levels, and mitigation codes using the predefined coding framework. Inter-coder agreement was assessed through iterative comparison of coding outputs. Discrepancies were resolved through structured consensus discussions informed by regulatory definitions, international EIA guidelines, and documented project evidence.

Where ambiguity persisted, conservative classifications were retained. This multi-coder, consensus-based approach enhances the transparency, robustness, and transferability of the proposed EIA-RMM system.

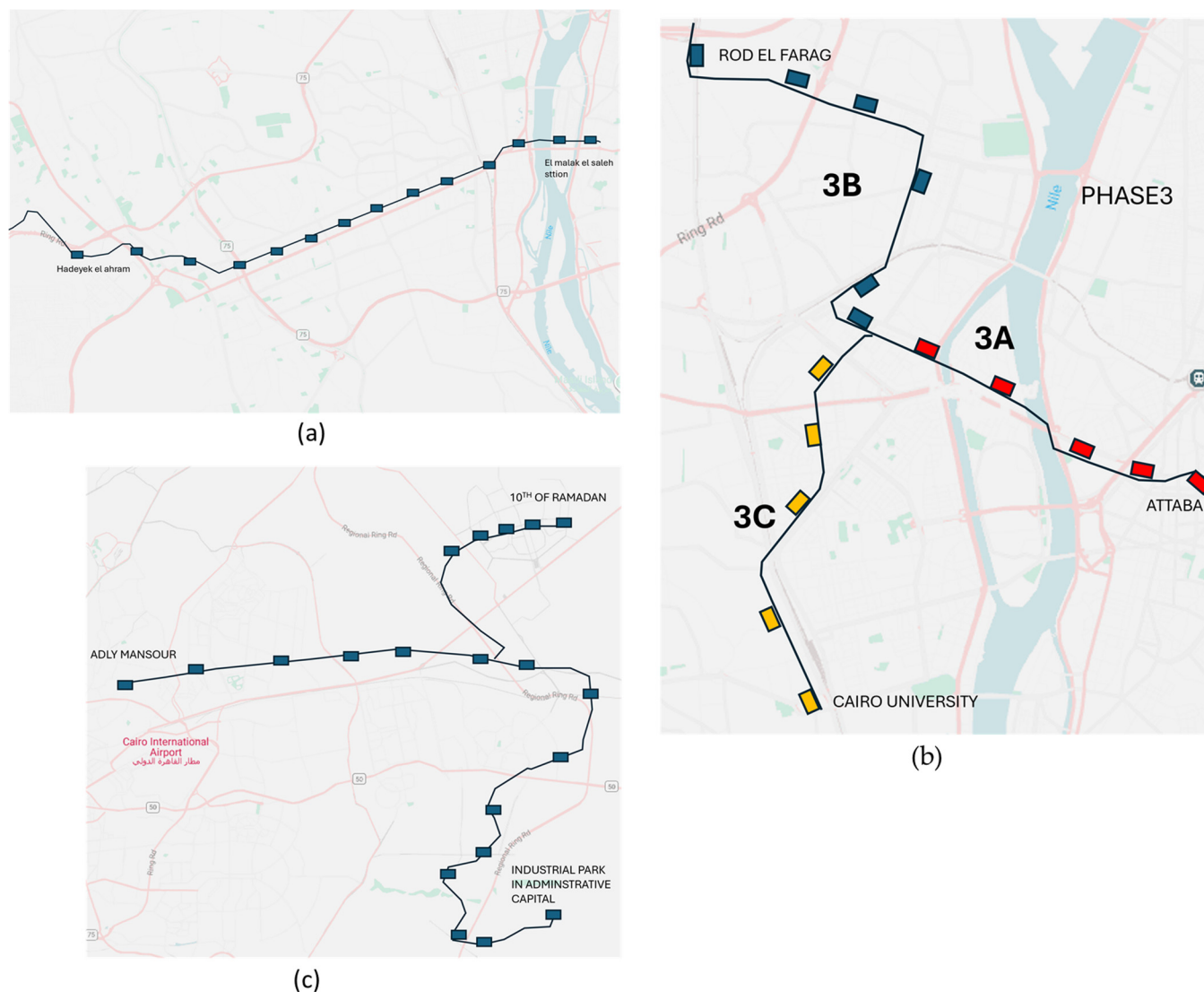


Figure 1. Case study projects, (a) Metro line 4 phase 1, (b) Metro line 3 phase 3, and (c) LRT route, developed by the authors based on [22,46].

After comparing the three case studies in terms of the applied mitigation measures, receptors and lifecycle phases, it was noticed that each of the EIA reports addressed different risks and that, through applying different mitigation measures, each report managed to decrease the significance of each impact. Figure 2 indicates minimization of the significance of risks across different project lifecycle phases. The figure indicates that all case studies managed to eliminate high risks, increase the percentage of negligible risks, and decrease the significance of each impact using corresponding mitigation measures.

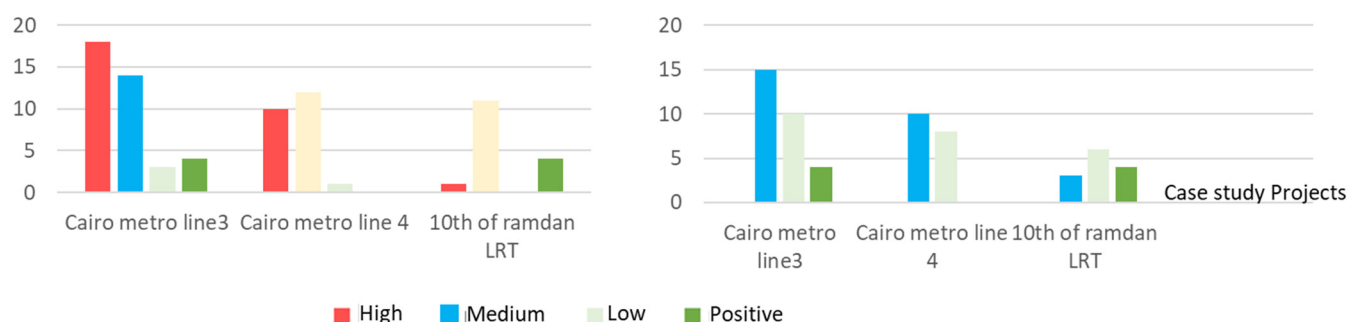


Figure 2. Risk assessment before and after applying the mitigation measures.

Nevertheless, this comparison also reveals notable variation in the scope and depth of impact coverage across the reviewed EIAs, suggesting differences in assessment priorities and reporting practices rather than systematic differences in project risk profiles. This highlights inconsistencies in how similar risks are addressed across projects, particularly with respect to monitoring requirements, institutional responsibility, and post-mitigation significance assessment. It is also noted that unassessed or undocumented risks may remain obscured within the comparative analysis. This comparison indicates that reductions in impact significance are not solely a function of mitigation effectiveness but are also influenced by differences in reporting completeness and risk disclosure, underscoring the need for standardized assessment and documentation frameworks.

3.2. Developing the Proposed Framework

For the purpose of this study, the model's interface has been developed using Airtable [47] to support a data repository and visualization backend. This is a cloud-based platform which serves as a flexible tool combining spreadsheet features with the power of a database [47]. The link to the developed model is <https://airtable.com/ap-pNQGyvwd6Lmm9MX/pagvINnodFzb6h31T>, accessed on 1 December 2025 and the full model can be found in the supplementary file.

3.2.1. Conceptual Design and Architecture of the Proposed Framework

The framework operates as a relational database structure built on modular components that represent key EIA elements: risks, receptors, mitigation measures, lifecycle phases, risk severity levels, and project metadata. These components are interconnected through linked records, lookup formulas, and conditional logic. The architecture functions as an integrated workflow (shown in Figure 3) in which project data is entered, automatically classified, cross-referenced through modules, and finally synthesized into analytics dashboards, comparative assessments, and structured risk-mitigation outputs.

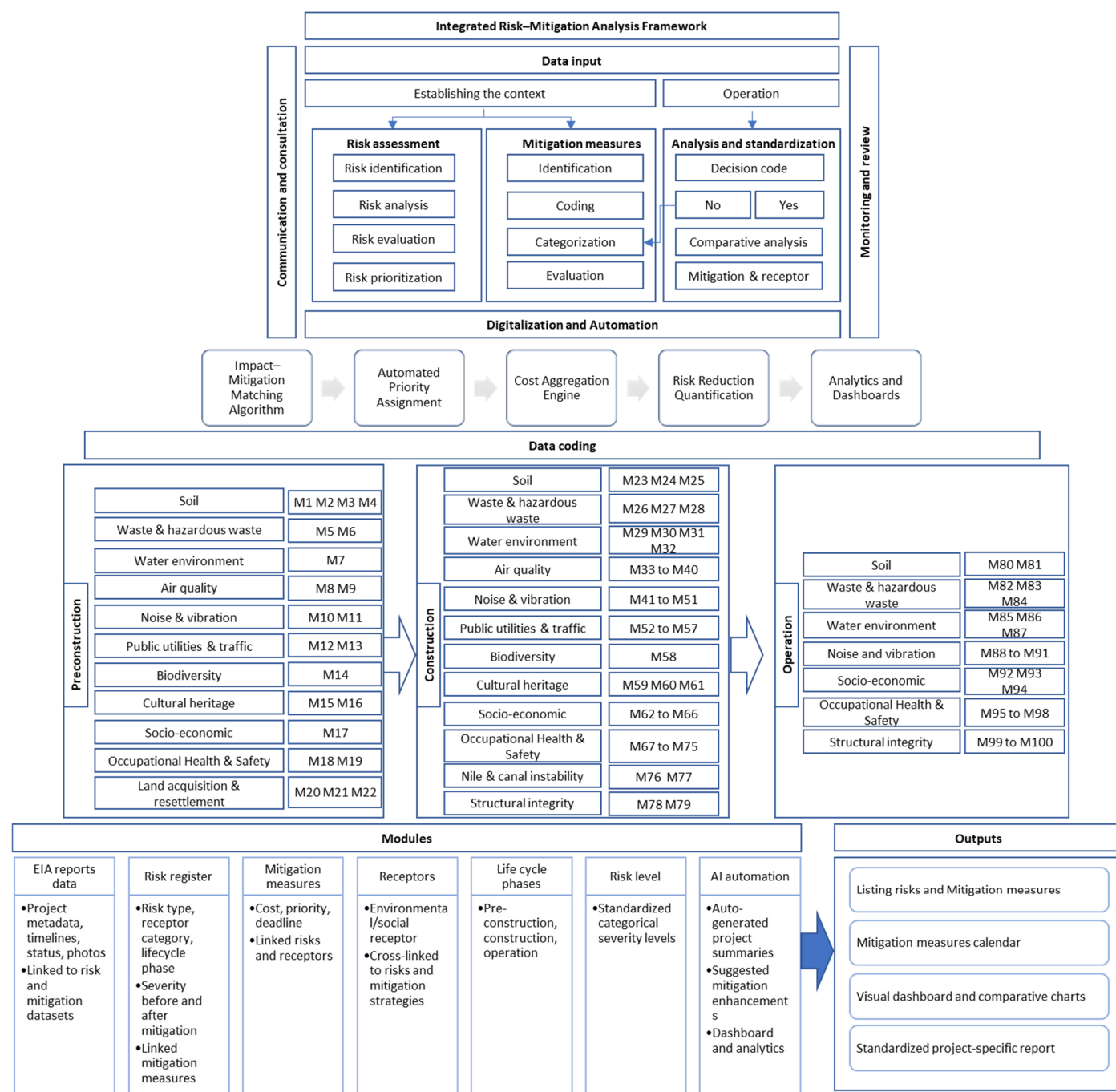


Figure 3. Conceptual design and architecture of the proposed framework.

3.2.2. Inputs and Modules

Input data can be entered through an Excel sheet to an AI chat agent which converts data directly to table modules, or the data can be entered manually in the module's tables. The inputs include project level inputs, risk inputs, mitigation inputs, and AI input parameters.

The project lifecycle module categorizes all risks and mitigation measures according to the three primary phases of project development: pre-construction, construction, and operation. This enables lifecycle-based evaluation and identification of phase-specific environmental hotspots.

The receptors module organizes all environmental and social receptors (e.g., soil, water, air quality, noise, and community health). Each receptor is linked to its associated

risks and mitigation measures, enabling receptor-based analysis and visualization of affected domains.

The risk register module functions as the analytical core of the system, storing all environmental and social risks identified in the EIA case studies. This module standardizes all risk severities using five recognized EIA categories: Major, Moderate, Minor, and Negligible, in addition to Positive Impacts only for the social impacts. These categories drive the automated priority-setting logic of the framework.

The framework links each risk to its corresponding project type, enabling cross-project comparison and severity mapping. It should be noted that instances where receptors or risks are reported as 'not addressed' in the reviewed EIAs do not necessarily indicate the absence of environmental or social impact. Rather, they often reflect differences in reporting scope, methodological rigor, or institutional practice across EIA documents. In this study, 'not addressed' categories were therefore treated as unreported rather than negligible and interpreted with caution in cross-project comparison. This approach avoids bias arising from uneven documentation and highlights reporting inconsistency itself as a significant governance challenge addressed by the proposed EIA-RMM framework.

The mitigation measures module documents all mitigation measures, along with cost, priority ranking, and implementation deadlines. Priority levels are generated through conditional logic based on risk severity, ensuring consistent and standardized decision-making. Each mitigation measure is linked to one or more risks, supporting automated generation of project-specific mitigation plans. Nevertheless, it should be noted that not all mitigation measures in the reviewed EIA reports are accompanied by clearly defined Key Performance Indicators (KPIs) at the time of assessment. This reflects prevailing practice in many EIAs, where mitigation is often described qualitatively and monitoring indicators are either under-specified or deferred to later project stages.

The EIA report data module compiles project-level information, including project type, duration, photographs, and status. It aggregates risks, mitigation measures, and cost summaries for each project, forming the basis of the comparative component of the framework.

The automation module integrates AI-generated text summaries, cost, and recommended additional mitigation measures. It also produces dynamic charts and dashboards used in impact interpretation. These dashboards present:

- Trends in risk severity.
- Risk distributions categorized by receptor.
- Phase-specific risk intensities.
- Cross-project comparisons.
- A mitigation measures calendar for tracking deadlines and implementation schedules.

The framework interface is shown in Figure 4 and more elaborately in Appendix A.6.

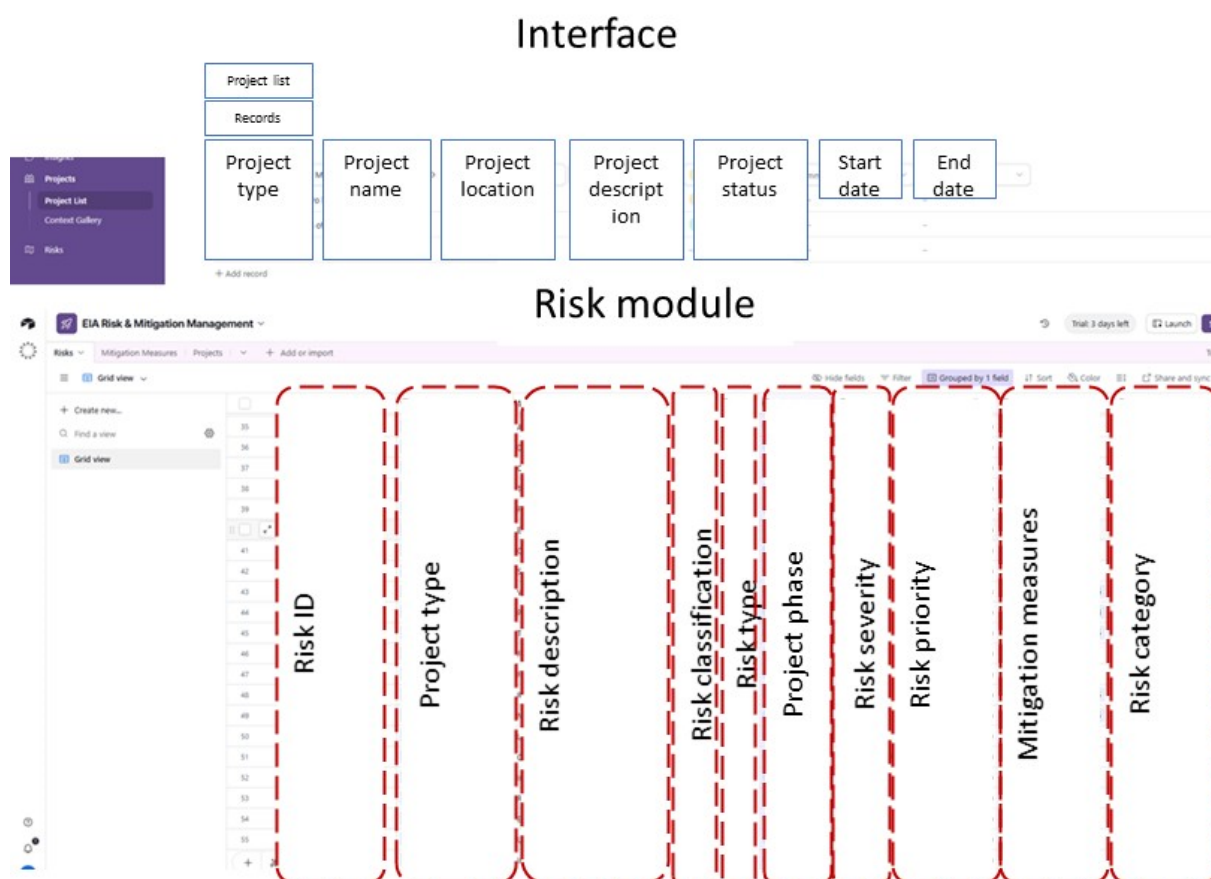


Figure 4. The proposed framework interface and risk module.

3.2.3. Digitalization and Automation

The following subsections describe the core processes embedded within the proposed framework.

The ‘Impact–Mitigation Matching Algorithm’ is a main feature in the proposed framework. In this regard, the system deploys a structured matching algorithm that automatically associates each identified risk with its corresponding mitigation measure. This is executed through linked records and lookup functions, ensuring that all mitigation actions reflect the characteristics of the risk, including impact type, affected receptor, and lifecycle phase. This automated alignment significantly reduces manual interpretation errors and supports consistency in cross-project analysis. To normalize cross-project comparison, risks not explicitly addressed in source EIAs are treated as unassessed rather than absent and are flagged by the system as documentation and compliance gaps, ensuring that variations in reporting completeness do not bias comparative conclusions.

The ‘Automated Priority Assignment’ is another significant feature of the proposed framework and is directly integrated with the MCDA/AHP decision hierarchy. In this regard, the proposed framework adopts an AHP-based hierarchy to structure decision criteria and a systematic aggregation of expert judgments, consistent with prior applications of AHP integration in sustainability-related decision-support studies [48,49]. This step aims to standardize the mitigation planning process through a conditional logic formula that assigns priority levels based on the severity of each identified risk. Risks classified as Major or Moderate are automatically assigned Priority 1, indicating urgent or high-importance actions. Minor risks are assigned Priority 2, while negligible risks are designated Priority 3.

The ‘Risk Reduction Quantification’ is another feature that enables a comparative assessment to quantify risk reduction achieved by applying mitigation measures. The

system analyzes severity levels before and after the mitigation process, presenting the results both numerically and visually. This allows users to evaluate the effectiveness of mitigation interventions, identify residual risks, and make informed decisions regarding the adequacy of proposed actions. The automated comparison ensures methodological consistency and facilitates monitoring of mitigation performance across the project timeline.

The 'Cost Aggregation Engine' is an automated cost aggregation mechanism that synthesizes financial data linked to mitigation measures. By receiving cost entries at the mitigation level and associating them with relevant risks and projects, the system automatically generates cumulative cost calculations. These include the total cost per project, total cost per receptor category, and other cost-based insights. This automation improves financial planning and supports the assessment of budget allocation for environmental management.

3.2.4. Sensitivity Analysis

To enhance the robustness of the process of mitigation planning, a sensitivity analysis was conducted following a validated approach previously applied in expert-driven MCDA studies to evaluate the ranking stability under varying weighting assumptions [50], as shown in Table 1. The analysis investigated three alternative schemes to calculate the weighted average of expert ratings within the AHP framework, as shown in Equations (1)–(4): (i) equal weighting of experts, where all experts contribute uniformly; (ii) experience-based weighting, where expert weights are proportional to years of professional and/or research experience; and (iii) familiarity-based weighting, where weights reflect each expert's self-reported level of familiarity with the assessed project type and impact category. The automated priority assignment was applied consistently across all three schemes, allowing for comparison of priority stability and identification of potential variations arising from expert weighting assumptions. The results indicate a high level of consistency in priority classification, confirming the reliability of the automated logic while also improving transparency and reducing subjectivity in environmental and social impact prioritization across different projects.

The aggregated ratings obtained from Equation (1), under each weighting scheme, are used as inputs to the AHP pairwise comparison matrices. The resulting criteria weights inform the automated priority assignment process, enabling comparison of priority stability across different expert-weighting assumptions.

$$\text{Aggregated rating: } \bar{r}_j = \sum (w_i \times r_{ij}), \sum w_i = 1 \quad (1)$$

$$\text{Equal weighting: } w_i = 1/n \quad (2)$$

$$\text{Experience-based weighting: } w_i = E_i / \sum E_i \quad (3)$$

$$\text{Familiarity-based weighting: } w_i = F_i / \sum F_i \quad (4)$$

where

$\bar{r}_j$ = the aggregated rating for criterion j ;

r_{ij} = the rating given by expert i to criterion j ;

w_i = the weight assigned to expert i ;

n = the total number of experts.

Table 1. AHP weighting.

Weighting Scheme	Basis of Expert Weighting	Observed Change in Criteria Weights	Stability of Priority Levels	Key Observation
Equal weighting	All experts weighted equally	Baseline reference	High	Serves as neutral benchmark with no expert bias
Experience-based weighting	Years of professional/research experience	Minor variation in secondary criteria	High	Senior experts slightly increased influence on technical risks
Familiarity-based weighting	Self-reported familiarity with project and impact type	Localized variation in context-specific criteria	High	Improved sensitivity to project-specific impacts

The aggregated ratings, $\bar{r}_j$, are used to construct the AHP pairwise comparison matrix as follows:

$$a_{jk} = \bar{r}_j / \bar{r}_k \quad (5)$$

The criteria priority vector, $p = [p_j]$, is obtained from the normalized principal eigenvector of matrix A as follows:

$$A p = \lambda_{\max} p \quad (6)$$

where $\lambda_{\max}$ is the maximum eigenvalue of matrix A.

The Consistency Index (CI) is calculated as:

$$CI = (\lambda_{\max} - m) / (m - 1) \quad (7)$$

The Consistency Ratio (CR) is then obtained by:

$$CR = CI / RI \quad (8)$$

where RI is the Random Index corresponding to matrix size m . A $CR < 0.10$ indicates an acceptable level of judgment consistency

The above procedure is repeated under the three expert-weighting schemes. Variations in the resulting priority vectors p and CR are analyzed to assess the robustness of the decision hierarchy and its influence on the automated priority assignment process. It was found that the calculated CR values consistently remained below the recommended threshold of 0.10, varying within a narrow range of 0.04 to 0.07. This limited dispersion indicates a high level of internal consistency in expert judgments, regardless of how expert influence is distributed within the aggregation process. Crucially, this consistency stability translates directly into robustness in the automated priority assignment outcomes. Although minor variations were observed in the relative importance of secondary criteria, the classification of risks as Priority 1, Priority 2, or Priority 3 remained unchanged across all sensitivity scenarios. This confirms that the proposed framework is resilient to subjective bias introduced by alternative expert-weighting assumptions and that the automated prioritization logic preserves decision coherence.

3.2.5. Outputs

The framework supports decision-making by structuring and prioritizing environmental and social information at key decision points and automatically links identified risks to precise, costed mitigation measures, producing a project-specific recommended mitigation list. This output includes crucial details like implementation priorities and phase-specific timelines. Furthermore, the quantified risk reduction index provides clear, measurable proof of the mitigation's effectiveness. Furthermore, the EIA-RMM framework produces standardized project-specific reports, including reports on project data, linked risks, mitigation measures and cost, as shown in Figures 5 and 6. Furthermore,

Appendix A.7 includes the data input for a case study project (Cairo Metro Line 3 Phase 3).

It does not generate alternative designs or spatial layouts directly; however, by systematically prioritizing high-significance impacts and linking them to specific mitigation logics, it provides structured environmental constraints that can guide alignment choices, infrastructure configurations, and construction planning decisions. In this way, the framework enhances the operational linkage between EIA findings and spatial design processes, transforming descriptive environmental assessments into decision-relevant inputs for infrastructure configuration and implementation.

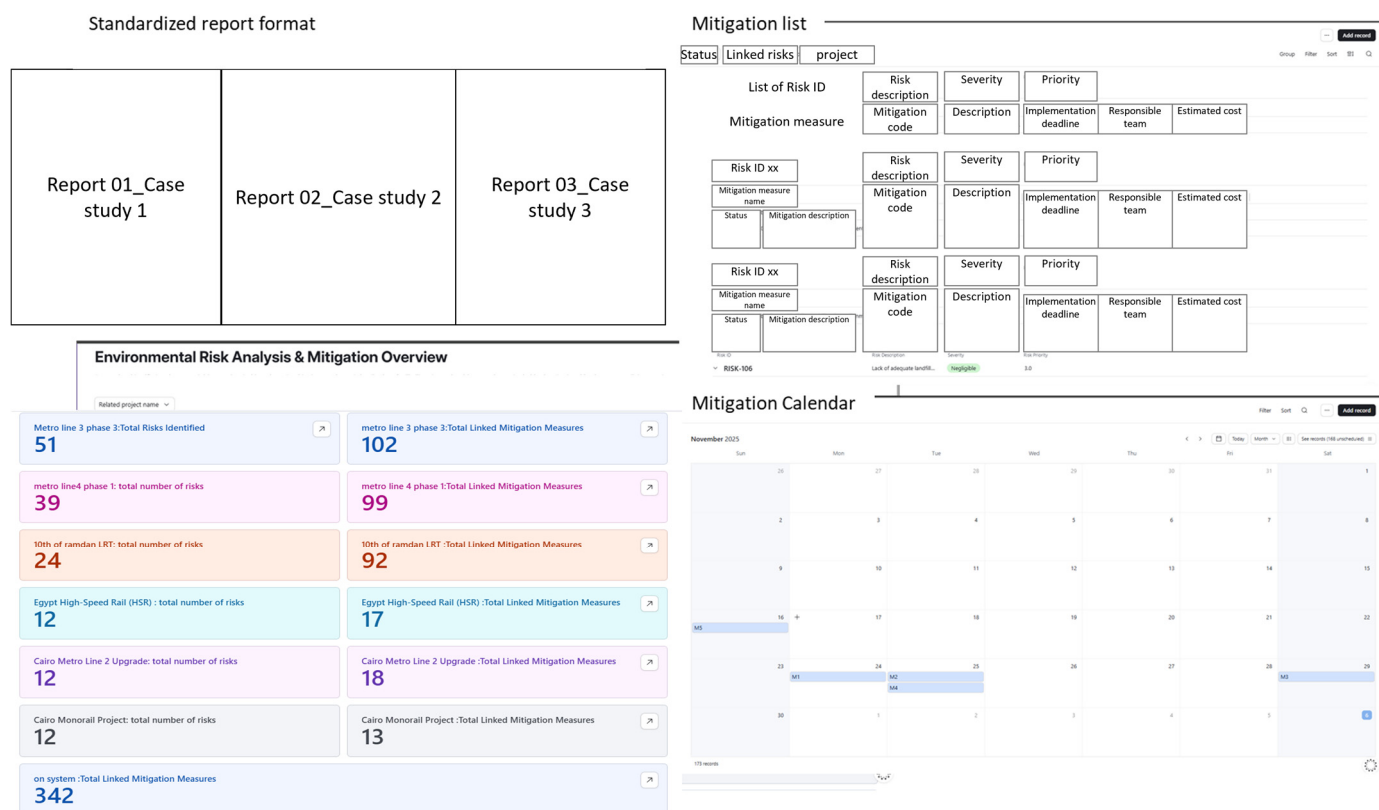


Figure 5. Output framework 1 showing the standardized report format for the three case studies, comparing their risks and mitigation measures and proposing a management calendar.

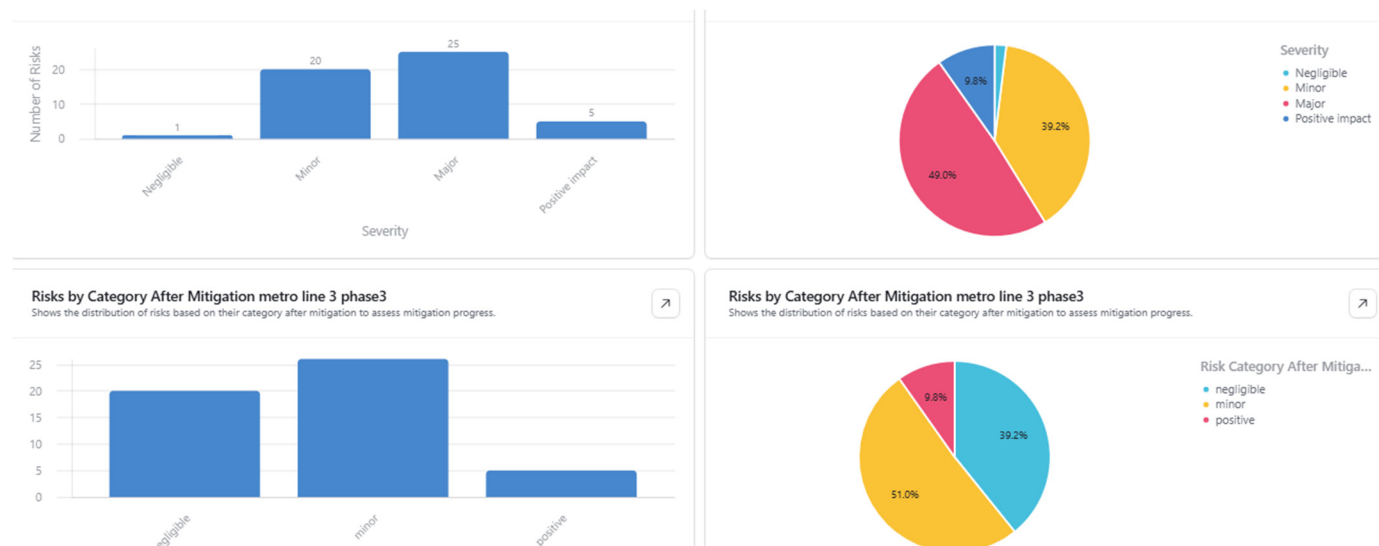


Figure 6. Output framework 2 comparing risks by severity and category across different project phases for a case study project, and the rest of the outputs are included in Appendix A.6.

For case study 1, the receptor analysis indicates several high-significance impacts linked directly to the project alignment and elevated infrastructure configuration, particularly in relation to noise, visual intrusion, cultural heritage, traffic disruption, and involuntary resettlement. These impacts arise from the proximity of the metro alignment to sensitive receptors, the vertical profile of the elevated sections, and the location of construction activities within dense urban corridors. Major noise and vibration impacts identified during both construction and operation phases would translate into spatial buffering requirements, alignment adjustments in sensitive zones, or the early integration of permanent noise barriers and vibration-isolation systems. Similarly, the identified visual and land-use impacts associated with elevated structures would prompt evaluation of alternative configurations, such as partial grade separation, context-sensitive architectural treatments, or enhanced landscape integration along affected segments. In addition, the major risks related to archaeological heritage and involuntary resettlement highlight areas where alignment optimization, micro-siting of stations, or phased construction strategies could reduce social and cultural impacts.

For case study 2, the receptor analysis highlights a series of moderate to major impacts closely associated with the project alignment, tunneling operations, and station locations within dense urban corridors. Key spatially driven impacts include vibration-induced settlement, traffic congestion, land acquisition, involuntary resettlement, and potential damage to archaeological resources, as well as the sensitive crossing beneath the Nile. These impacts are inherently linked to alignment depth, station placement, construction staging areas, and the spatial relationship between the infrastructure and surrounding receptors. Within the proposed framework, such impacts were classified as high-priority, design-sensitive risks, prompting early consideration of alignment alternatives, micro-siting of stations, and adjustments to tunneling methods in sensitive zones. For example, moderate vibration and settlement risks would translate into alignment optimization, geotechnical zoning, and the selection of construction techniques that minimize ground disturbance. Similarly, major resettlement and land occupation impacts would function as triggers for locational adjustments, station footprint reduction, or phased construction strategies to reduce displacement and maintain urban continuity. The identified congestion and utility diversion impacts inform the spatial organization of construction sites, access routes, and temporary infrastructure, encouraging the use of alternative alignments, temporary bridging structures, or decentralized staging areas. In addition, the moderate risk associated with tunneling beneath the Nile would be treated as a critical alignment-sensitive constraint, guiding the selection of tunnel depth, crossing location, and structural reinforcement strategies based on geotechnical risk zoning and monitoring requirements.

For case study 3, the receptor analysis indicates predominantly minor to moderate impacts associated with construction activities, traffic interactions, occupational risks, and localized environmental disturbances along the alignment. Compared to the dense urban contexts of the metro case studies, the LRT project is characterized by fewer high-severity receptors and a larger share of neutral or positive socio-economic and environmental outcomes, particularly during operation. Nevertheless, several impacts—such as soil erosion, construction dust, traffic interference, and occupational safety risks—remain directly linked to alignment corridors, construction staging areas, and the spatial interaction between project infrastructure and surrounding activities. Within the proposed framework, these impacts were categorized as moderate-priority, location-sensitive risks, informing decisions related to corridor selection, construction logistics, and infrastructure detailing.

For example, moderate soil erosion and dust impacts would translate into alignment-specific drainage strategies, controlled material storage zones, and optimized routing of construction traffic to reduce disturbance in sensitive areas. Similarly, the identified traffic interaction risks during construction would inform the spatial organization of equipment movement, access roads, and temporary staging areas to minimize conflicts with existing or concurrent development projects. Operational-phase impacts, including noise, vibration, and increased traffic around stations, would function as triggers for context-sensitive infrastructure configurations, such as the integration of vibration-absorption systems, noise-reducing track components, and improved station-area circulation planning. At the same time, the predominantly positive socio-economic and environmental impacts associated with the LRT system—such as reduced emissions, improved mobility, and economic stimulation—would support the strategic placement of stations and alignment segments in areas targeted for future urban development.

Across the three case studies, the receptor analyses show how environmental risks are closely linked to alignment choices, station locations, and construction configurations, but with varying levels of severity depending on context. In the dense urban metro projects (Lines 3 and 4), high- and moderate-significance impacts—such as noise, vibration, visual intrusion, resettlement, traffic disruption, and archaeological risks—are directly tied to infrastructure geometry and proximity to sensitive receptors. In these cases, the framework would operate primarily as a design-constraint mechanism, guiding alignment refinements, spatial buffering, tunneling strategies, and station siting to minimize social and environmental impacts. By contrast, the 10th of Ramadan LRT, located in a less constrained and more development-oriented context, presents mainly minor to moderate impacts and several positive operational effects. Here, the framework would function more as a spatial optimization tool, informing corridor management, construction logistics, and strategic station placement to support planned urban growth. Overall, the comparison demonstrates that the framework consistently converts descriptive EIA data into structured decision inputs, while its spatial influence adapts to project context—ranging from risk-sensitive alignment adjustments in dense urban areas to development-oriented configuration guidance in lower-impact environments.

4. Discussion

The present study, in addressing the current topic, is relevant and timely, as it tackles one of the main weaknesses of contemporary EIA practice: the difficulty of translating complex environmental assessments into tools that effectively manage and guide the decision-making process. Thus, the study proposes a structured system that moves beyond the purely descriptive and document-based nature of many impact studies. It is noted that the proposed framework is best used as a tool for environmental impact management. Its contribution is strongly oriented toward procedural, managerial, and monitoring aspects. Nevertheless, the framework is less developed as a device capable of directly informing design decisions. It does not directly model infrastructure geometry; nevertheless, it strengthens the integration between environmental analysis and physical configuration by translating risk classification and mitigation priorities into design-relevant constraints and performance requirements that can inform alignment choices, construction methods, and protective infrastructure decisions within existing design workflows.

The EIA-RMM framework is designed as a predominantly rule-driven decision-support system. Its key operations—such as linking risks to mitigation measures, assigning priority levels, and aggregating costs—are implemented through clearly defined conditional rules and MCDA/AHP calculations grounded in expert knowledge and established evaluation criteria, which were further investigated using a sensitivity analysis. AI is used in an auxiliary capacity to facilitate data organization, process automation, and analytical

summarization, rather than to perform autonomous learning or decision-making. This design ensures that system outputs remain transparent, repeatable, and verifiable.

The analysis further indicates that several mitigation measures across the reviewed EIAs lack clearly defined performance indicators at the outset, reflecting a broader tendency toward qualitative rather than performance-based mitigation planning. Within the proposed EIA-RMM framework, such measures are explicitly flagged as requiring KPI definition, thereby supporting more transparent monitoring, accountability, and adaptive management over the project lifecycle.

Nevertheless, the proposed framework is subject to inherent limitations. The functionality of the AI automation module, including suggested mitigation enhancements and predictive risk scoring, relies entirely on the quality and consistency of historical EIA data used for training and operational input. This necessitates a significant upfront investment in data cleaning, normalization, and verification, establishing a continuous feedback loop in which improved input report quality directly enhances the framework's reliability and outcome results. Another limitation is that the evaluation of the proposed EIA-RMM framework is based on its analytical performance using existing EIA data, without independent verification through post-implementation monitoring or third-party compliance audits.

A comparison of the findings with those of previous studies is shown in Table 2.

Table 2. Comparison of the findings with those of previous studies.

Aspect	Findings of This Study	Findings from Previous Studies	Key Added Value of This Study
Role of EIA in project decision-making	Demonstrates that EIA outputs often remain descriptive unless translated into structured decision-support logic; proposes a digital framework to operationalize EIA findings across project phases.	EIAs frequently function as compliance documents with limited influence on design and implementation decisions [24,51].	Moves beyond diagnosis by providing a structured system that links EIA outcomes to decision priorities and implementation logic.
Identification of environmental risks	Reveals uneven identification of environmental receptors and risks across case studies, largely driven by reporting practices rather than actual risk absence.	Prior studies noted variability and inconsistency in EIA scoping and impact identification [52,53].	Explicitly treats missing risks as 'unassessed' rather than absent, improving cross-project comparability.
Mitigation measures and effectiveness	Finds that mitigation measures are frequently defined qualitatively, with limited use of measurable KPIs; highlights this as a governance and implementation gap.	Mitigation effectiveness is often weakly monitored and poorly linked to performance indicators [15,24].	Introduces a framework that flags mitigation measures lacking KPIs and supports performance-based monitoring.
Integration with design and construction	Shows that mitigation priorities can inform design-relevant constraints (e.g., avoidance, buffering, sequencing) but are rarely embedded systematically in design workflows.	Weak integration between EIA and engineering design is a recurring limitation in infrastructure projects [52,54,55].	Clarifies a procedural pathway for embedding environmental requirements into design and construction decision-making without automating design.
Use of digital and AI-based tools	Positions AI as an assistive, rule-based decision-support component for structuring, prioritizing, and managing EIA data.	Digital tools in EIA are often exploratory or predictive, with limited transparency and regulatory acceptance [52,54,56].	Demonstrates a transparent, rule-based digital approach suitable for regulatory EIA contexts.
Transferability across projects	Emphasizes transferability of decision logic and mitigation structures rather than project-specific solutions.	Transferability of EIA lessons is often limited by contextual and regulatory differences [57].	Abstracts EIA knowledge into standardized categories and workflows that can be adapted across contexts.

Governance and reporting quality	Identifies inconsistent reporting itself as a critical governance issue affecting EIA reliability and comparison.	Previous research highlights institutional and procedural weaknesses in EIA systems [34,57].	Treats reporting gaps as analytical outputs, reinforcing the role of structured systems in improving EIA governance.
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This shows the key added value of the research and its scientific contribution.

5. Conclusion and Directions for Future Research

The study responds to a persistent limitation in contemporary EIA practice—namely, the challenge of translating complex environmental assessments into structured tools that meaningfully inform project decision-making and infrastructure management. It also addresses other challenges, including the fragmented documentation of risks, the variable quality of mitigation measures, and the difficulty of comparing outcomes across projects. By proposing a systematic framework, the study moves beyond the predominantly descriptive and document-centric character of many existing impact assessments. Thus, the primary objective of the proposed EIA-RMM framework is to establish a standardized, data-driven framework capable of identifying environmental and social risks, assigning appropriate mitigation measures, identifying and quantifying risk reduction, and supporting decision-makers across the entire project lifecycle. It does not generate design solutions; instead, it supports decision-making by identifying, structuring and prioritizing environmental and social information at key decision points.

- Before design (early planning and scoping): the framework supports the identification and prioritization of key environmental and social risks, enabling early avoidance strategies, alternative alignment considerations, and the definition of environmental constraints before major design commitments are made.
- During design (design development and detailing): the framework informs design decisions by translating prioritized risks and mitigation requirements into design constraints, performance criteria, and implementation priorities, supporting choices related to layout, construction methods, material specifications, and protective infrastructure.
- After design (construction and operation): the framework continues to support decision-making by tracking mitigation implementation, monitoring compliance, and enabling comparison between planned and implemented measures.

The core contributions of the proposed framework are:

- Standardization and efficiency for risk identification, categorization, and efficient cross-project auditing, enabling regulatory bodies to review and compare projects rapidly and consistently.
- It enables comparing risk severity before and after mitigation, offering a quantified risk reduction index that demonstrates mitigation effectiveness.
- It converts static reports into dynamic, actionable components, producing a structured environmental and social management plan with clear mitigation actions, priorities, cost allocation, and phase-specific timelines.
- It enables standardized EIA implementation, auditing, review, monitoring, evaluation and enables efficient cross-project comparisons.

For official, governmental and regulatory bodies, the framework can function as a centralized portfolio risk management and strategic planning system. It can be used to identify systemic, sector-wide risk trends and prioritize mitigation measures based on consistent, automated priority assignments. Dynamic dashboards provide high-level analytics, visualizing risk distributions and cost requirements, which is crucial for

ministerial monitoring and strategic decision-making regarding future infrastructure development.

For EIA consultancy firms, the proposed framework serves as a knowledge base and quality assurance framework for report generation. The platform enables leveraging of standardized datasets and referencing historical data to identify proven mitigation strategies and standardized risk categorizations, thereby saving time and reducing variability in report quality. The framework's automated processes, such as the Impact–Mitigation Matching Algorithm and the conditional logic for priority assignment, enforce a high consistency level.

Future development can incorporate AI enhancement, integrating advanced features like Natural Language Processing for automated risk extraction and Machine Learning for predictive risk scoring. Also, addressing concerns associated with software interoperability is crucial for ensuring seamless data exchange with industry-standard tools such as BIM software, project management systems and simulation programs. Future research can help develop the proposed framework to support the evaluation of different design alternatives and accompany the implementation and monitoring phases. More research can contribute by addressing the major gap between specified mitigation measures versus those implemented, which highlights poor compliance and decoupling between theory and practice in Egypt as well as other developing countries.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/su18041980/s1>, Video S1: The proposed model.

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Appendix A

Appendix A.1. Case Study 1: Cairo Metro Line 3 Phase 3

Table A1. Receptor analysis (Cairo Metro Line 3 Phase 3), developed by the authors based on [45].

Environmental/Social Receptor	Project Phase	Identified Impact	Significance (Pre-Mitigation)
Soil	Pre-construction	Soil contamination due to spills/disposals	Minor
	Construction	Soil compaction due to heavy machinery	Minor
		Soil disturbance due to construction activities	
	Operation	Soil contamination due to spills/disposals	Minor
Waste and hazardous waste	Pre-construction	Soil disturbance due to leakage/vibration	Minor
	Construction	Lack of adequate landfill sites and long transport routes	Negligible
	Operation	Low capacity for waste handling produced soil excavated waste, earthwork waste, wastewater, and machinery fuel and oils	Major
	Operation	Generated operation waste	Minor

Water environment	Pre-construction	Groundwater contamination	Minor
	Construction	Structure changes in both surface water/groundwater Groundwater contamination	Minor
	Operation	Groundwater contamination due to ineffective spills of oil and fuel	Minor
Dust and air quality	Pre-construction	Vehicle and machine emissions Transportation resulted in dust	Major
	Construction	Vehicle and machine emissions Construction resulted in dust	Major
	Operation	Reduction in bad emissions due to use of electric energy in metro	Positive impact
Noise	Pre-construction	Pre-construction work noise	Major
	Construction	Construction work noise	Major
	Operation	Noise during operating hours of metro	Major
Vibration	Pre-construction	Onsite work vibration from different machines Transportation vibration	Minor
	Construction	Onsite work vibration from different machines Transportation vibration	Minor
	Operation	Vibration during operating hours	Minor
Visual and functional intrusion /land-use change and aesthetic damage	Pre-construction	Re-vegetation and landscaping issues Bad visual impression due to elevated metro line design	Major
	Construction	Engraving green areas on construction sites Unmaintained urban facilities Visual disturbance due to construction work on site	Major
	Operation	Poor commitment to regreening and revitalizing impacted urban areas	Major
Biodiversity and nature conservation	Pre-construction	Impact on habitat and vegetation	Minor
	Construction	Impact on habitat and vegetation	Minor
	Operation	No impact	Negligible
Archaeological and cultural heritage	Pre-construction	Damage to buried artifacts/historical buildings	Major
	Construction	Damage to buried artifacts/historical buildings	Major
	Operation	No impact	Negligible
Public utilities and traffic	Pre-construction	Missing implementation of rerouted traffic plans	Major
	Construction	Congestion on construction sites/route closure and decreased route capacities due to site work	Major
	Operation	Reduction in reliance on other means of transport	Minor
Urban development /loss of land and property	Pre-construction	-	-
	Construction	-	-
	Operation	Encroachment on agricultural land for urban usage around ring road Community character changes	Minor
Involuntary re-settlement and	Pre-construction	-	-

vulnerable groups	Resettlement		
	Construction	Disturbance of activities and services along the metro line alignment	Major
	Operation	-	-
Socio-economic effects	Pre-construction	Offering job opportunities and enhancing incomes Unskilled workers' involvement in construction process	Positive impact
	Construction	Offering job opportunities and enhancing incomes Unskilled workers' involvement in construction process	Positive impact
	Operation	High mobility of workers leads to enhanced incomes	Positive impact
Labor standards and occupational health and safety	Pre-construction	Risk on construction site	Major
	Construction	Risk on construction site	Major
	Operation	Risks resulted from poor implementation of (International Labour Organization) rules	Major
Community health and safety	Pre-construction	-	-
	Construction	-	-
	Operation	Communities surrounding the project impacted by noise, dust and air quality	Major
Nile and canal instability	Not addressed		

Table A2. Mitigation measures in the pre-construction phase (Cairo Metro Line 3 Phase 3), developed by the authors based on [45].

Project Phase	Environmental/Social Receptor	Proposed Mitigation Measures	Responsible Party	Monitoring/Follow-Up	Significance (After Mitigation)
Pre-Construction	Soil	Develop soil handling & spill management plan; store & dispose of waste properly; monitor vibration and conduct building surveys.	Contractor (supervised by NAT)	Inclusion in environmental and social management planning manual before construction.	Negligible
	Waste & Hazardous Waste	Agree on landfill/dumping sites; prepare Waste Management Plan.	NAT & contractor	Plan reviewed and approved prior to work.	Negligible
	Water Environment	Maintenance plan for construction machinery.	Contractor under NAT supervision	Monitoring plan implemented.	Negligible
	Air Quality & Dust	Develop Dust Management Plan; install ambient air quality monitoring.	Contractor	Regular monitoring; results reported.	Minor
	Noise & Vibration	Baseline survey; noise/vibration monitoring program.	Contractor & NAT	Periodic monitoring.	Minor
	Public Utilities & Traffic	Develop detailed utility and traffic deviation plans.	NAT & authorities	Plans approved before construction started.	Minor

Biodiversity / Visual Intrusion	Re-vegetation & urban facility plans agreed before work.	NAT & local authorities	Plans approved by authorities.	Negligible
Cultural Heritage	Conduct additional risk studies; implement chance-find procedure.	NAT & Project Implementation Unit	Procedure documented and ready.	Minor
Socio-Economic	Encourage use of local labor.	NAT	Monitored through HR reports.	Positive impact
Occupational Health and Safety (OHS) (Labor Standards)	Develop OHS Policy & Emergency Response Plan; staff training.	Contractor & NAT	OHS Plan reviewed before mobilization.	Minor
Land acquisition and resettlement	Not addressed			

Table A3. Mitigation measures in the construction phase (Cairo Metro Line 3 Phase 3), developed by the authors based on [45].

Project Phase	Receptor	Mitigation Measures	Responsible Party	Monitoring/Follow-up	Significance (After-Mitigation)
Construction	Soil	Develop and implement Waste Management Plan; spill management procedures; monitor vibration and building condition along alignments.	Contractor (supervised by NAT)	Implementation reports and vibration monitoring records.	Negligible
	Waste & Hazardous Waste	Maintain Waste Registers; coordinate with Cleansing Authorities; ensure proper storage, transport, recycling, and licensed disposal.	Contractor & NAT	Waste logbooks and inspection records.	Minor
	Water Environment	Apply strict spill prevention; protect watercourses; prevent illegal dumping; monitor groundwater and drainage quality.	Contractor under NAT supervision	Water quality monitoring results and spill reports.	Negligible
	Air Quality	Implement Dust Management Plan; use low-emission (EURO V) machinery; apply diesel particulate filters; conduct air quality monitoring.	Contractor & NAT	Daily inspections and monitoring logs.	Minor
	Noise & Vibration	Schedule noisy work for daytime; install temporary noise barriers; continuous monitoring; conduct noise impact study; install permanent barriers if required.	Contractor & NAT	Noise and vibration monitoring reports; compliance audits.	Minor
	Visual & Urban Intrusion	Apply urban design and beautification measures; implement context-sensitive planning; re-establish green areas after work.	NAT	Field verification and authority approval.	Minor

Biodiversity	Replant trees and restore vegetation immediately after completion.	Contractor & NAT	Site inspections and replanting verification.	Negligible
Cultural Heritage	Conduct detailed archaeological study; implement chance-find procedure; ensure archaeologist present during excavation.	NAT & Project Implementation Unit	Archaeological supervision reports.	Minor
Public Utilities & Traffic	Prepare and implement Traffic Management Plan; coordinate with relevant authorities for diversions and restoration.	Contractor & NAT	Traffic deviation and coordination records.	Minor
Socio-Economic	Hire local labor; maintain access routes; coordinate with affected businesses; communicate construction schedules.	NAT	Community liaison reports and Grievance Redress Mechanism documentation.	Positive
OHS & Community Health	Enforce OHS standards (International Labour Organization-compliant); provide Personal Protective Equipment (PPE), training, and Emergency Response Plan; continuous noise, air, and dust monitoring; community engagement.	Contractor & NAT	Audit reports, training logs, and monitoring results.	Minor

Table A4. Mitigation measures in the operation phase (Cairo Metro Line 3 Phase 3), developed by the authors based on [45].

Project Phase	Receptor	Mitigation Measures	Responsible Party	Monitoring/Follow-up	Significance (After Mitigation)
Operation	Soil	Develop spill management procedures; monitor vibrations and building stability along alignments.	Environmental Control Manager (ECM)	Maintenance and inspection logs.	Negligible
	Waste Management	Implement operational Waste Management Plan; ensure segregation, recycling, and proper disposal.	ECM	Waste records and environmental audits.	Negligible
	Water Environment	Maintain drainage systems; monitor groundwater and wastewater; enforce spill prevention protocols.	ECM	Routine inspection and water monitoring reports.	Negligible
	Noise & Vibration	Regular maintenance of rails, wheels, and rolling stock; periodic noise/vibration monitoring at sensitive receptors.	ECM	Noise and vibration monitoring data.	Minor
	Visual / Urban Aesthetics	Maintain landscaping and station aesthetics; coordinate with local authorities for upgrades.	ECM & local authorities	Field inspection and maintenance records.	Minor
	Socio-Economic	Maintain reliable service; uphold safety and accessibility; ensure	ECM	Passenger satisfaction surveys;	Positive

	effective public communication and grievance redress.		incident and complaint reports.	
OHS & Community Health	Implement Emergency Response Plan; conduct staff safety training and emergency drills; update health and safety procedures.	ECM	Safety audits, emergency drill reports, and training logs.	Minor

Appendix A.2. Case Study 2: Cairo Metro Line 4 Phase 1

Table A5. Receptor analysis (Cairo Metro Line 4 Phase 1), developed by the authors based on [22].

Environmental/Social Receptor	Project Phase	Identified Impact	Significance (Pre-Mitigation)
Soil	Pre-construction and construction	Excavation of soil Waste disposal Oil spills	Minor
	Operation	Pollution due to oil leakage and wastewater	Minor
Waste and hazardous waste		Not addressed	
Water environment	Pre-construction and construction	Change in groundwater characteristics and quality due to: excavation of soil, waste disposal and oil spills	Minor
	Operation	Groundwater pollution due to oil leakage and wastewater	Minor
Dust and air quality	Pre-construction and construction	Vehicle and machine emissions Dust resulted from soil excavation and handling	Moderate
	Operation	Secondary impact resulted from emissions of other vehicles attracted to metro stations	Minor
Noise	Pre-construction and construction	Noise resulted from machinery and vehicles	Minor
	Operation	Primary impact of noise during operating hours of metro Secondary impact resulted from noise of other vehicles attracted to metro stations	Minor
Vibration	Pre-construction and construction	Vibration leads to land settlement	Moderate
	Operation	Vibration during operating hours	Moderate
Visual and functional intrusion /land-use change and aesthetic damage	Pre-construction and construction	Dust and storage of waste Temporary structures and machinery	Minor
	Operation	Secondary impact due to land-use changes due to new activities attracted to stations, such as commercial activities	Minor
Biodiversity and nature conservation	Pre-construction and construction	Air and noise emissions Clearance, excavation work and leveling	Moderate
	Operation	Emissions, vibration and noise Disposal of solid wastes	Negligible
Archaeological and cultural heritage	Pre-construction and construction	Dewatering, vibrations, boring and excavation may lead to damage	Moderate
	Operation	Not addressed	

Public utilities and traffic	Pre-construction and construction	Congestion and occupation of width of roads Diversion of utilities	Moderate
	Operation	Traffic congestion resulted from attracted vehicles to metro stations	Minor
Urban development /loss of land and property	Pre-construction and construction	Temporary or permanent land and property acquisition	Moderate
	Operation	Not addressed	
Involuntary resettlement and vulnerable groups		-	
	Pre-construction and construction	Land occupation Physical barriers due to activities along the metro construction Noise and air pollution Traffic congestion	- Major
	Operation	Not addressed	
		Not addressed	
Socio-economic effects		Not addressed	
Labor standards and occupational health and safety	Pre-construction and construction	Falls, slips and injuries Emissions, vibrations, heat and noise	Moderate
	Operation	Falls, slips and injuries Emissions, vibrations, heat and noise	Minor
Community health and safety	Pre-construction and construction	Emissions, vibrations, and noise Risks due to machinery and vehicles	Moderate
	Operation	Emissions, vibrations, and noise	Minor
Nile and canal instability	Pre-construction and construction	Crossing under the Nile	Moderate
	Operation	Not addressed	

Table A6. Mitigation measures in the pre-construction phase (Cairo Metro Line 4 Phase 1), developed by the authors based on [22].

Project Phase	Environmental/Social Receptor	Proposed Mitigation Measures	Responsible Party	Monitoring/Follow-Up	Significance (After-Mitigation)
Pre-Construction	Soil				
	Waste & Hazardous Waste				
	Water Environment			Not addressed	
	Air Quality & Dust				
	Noise & Vibration				
	Public Utilities & Traffic	Keep utilities working in good condition by: supporting temporary or permanent diversions	NAT	Approved relocation plans and monitoring during early work and meetings	Minor
	Biodiversity / Visual Intrusion				
	Cultural Heritage			Not addressed	
	Socio-Economic				
	OHS (Labor Standards)				
	Land Acquisition and Resettlement	Apply compensation	NAT/Ministry of Transport	Surveying authorities	Minor

Apply resettlement
PAPS consultation

Table A7. Mitigation measures in the construction phase Cairo Metro Line 4 Phase 1), developed by the authors based on [22].

Project Phase	Receptor	Mitigation Measures	Responsible Party	Monitoring/Follow-Up	Significance (After-Mitigation)
Construction	Soil	Implement spill control and soil management procedures; monitor vibration and building stability.	Contractor (under NAT supervision)	Site inspections and vibration monitoring reports.	Negligible
	Waste & Hazardous Waste		Not addressed		
	Water Environment	Apply spill prevention and containment; monitor groundwater and drainage quality; prohibit illegal discharges and control of erosion.	Contractor under NAT supervision	Water quality monitoring results and inspection reports.	Negligible
	Air Quality	Implement Dust Management Plan; use low-emission machinery; install particulate filters; monitor air quality; correct disposal of excavated materials.	Contractor & NAT	Daily inspections and ambient air monitoring records.	Negligible
	Noise & Vibration	Restrict noisy work to daytime; use noise barriers; continuous monitoring; install permanent barriers if required, use special equipment, schedule truck work.	Contractor & NAT	Noise/vibration monitoring reports and compliance audits.	Minor (noise) Negligible (vibration)
	Visual & Urban Intrusion		Not addressed		
	Biodiversity		Not addressed		
	Cultural Heritage	Implement chance-find procedure; conduct archaeological supervision during tunneling. Non-destructive surveying.	NAT & contractor	Archaeological supervision and reporting.	Minor
	Public Utilities & Traffic	Temporary steel structures as a substitute for vehicle movement, managing alternative routes.	Contractor & NAT	Traffic coordination and deviation records.	Minor
	Socio-Economic	Maintain access routes; communicate with affected shops; prioritize local labor, apply pedestrian crossings, planning for services and activities, provide training for work.	Contractor and NAT	Community liaison reports and records.	Minor
	OHS & Community Health	Enforce OHS standards; provide PPE, training, and Emergency Response Plan; engage communities, fire extinguishers, correct storage for flammable materials, adhere to public health and safety standards.	Contractor & NAT	Audit reports, training records, and environmental monitoring results.	Minor

Nile and Canal Instability	Geotechnical surveys, work in coordination with Nile Research Institute.	NAT	Supervision by Nile Research Institute	Minor
Structural Integrity	Application of risk categorization zones, settlement numerical analysis.	Contractor & NAT	Monitoring reports and compliance audits.	Minor

Table A8. Mitigation measures in the operation phase (Cairo Metro Line 3 Phase 3), developed by the authors based on [45].

Project Phase	Receptor	Mitigation Measures	Responsible Party	Monitoring/Follow-Up	Significance (After-Mitigation)
Operation	Air Quality		Not addressed		
	Waste Management	Implement operational Waste Management Plan; ensure segregation, recycling, and proper disposal.	ECM	Waste records and environmental audits.	Negligible
	Water Environment	Maintain drainage systems; monitor groundwater and wastewater; enforce spill prevention protocols.	ECM	Routine inspection and water monitoring reports.	Negligible
	Noise & Vibration	Regular maintenance of rails, wheels, and rolling stock; periodic noise/vibration monitoring at sensitive receptors.	ECM	Noise and vibration monitoring data.	Negligible
	Visual / Urban Aesthetics		Not addressed		
	Socio-Economic		Not addressed		
	OHS & Community Health	Implement Emergency Response Plan; conduct staff safety training and emergency drills; update health and safety procedures.	ECM	Safety audits, emergency drill reports, and training logs.	Negligible
	Structural integrity	Vibration absorption equipment and proper engineering design.	ECM	Vibration monitoring data.	Minor

Appendix A.3. Case Study 3: 10th of Ramadan LRT

Table A9. Receptor analysis (10th of Ramadan LRT), developed by the authors based on [46].

Environmental/Social Receptor	Project Phase	Identified Impact	Significance (Pre-Mitigation)
Soil	Pre-construction and construction	Soil erosion due to disposal, earthworks, drainage and oil leaks	Moderate/Minor
	Operation	Soil pollution due to maintenance work	Minor
Waste and hazardous waste	Pre-construction and construction	Not addressed	
	Operation		
Water environment		NA	
Dust and air quality	Pre-construction and construction	Vehicle and machine emissions Transportation resulted in dust	Moderate/minor

		Construction resulted in dust	
		Dust that resulted from other transportation vehicles attracted to it	Minor
		Maintenance resulted in dust	
	Operation	Reduction in bad emissions due to using alternative environmentally friendly modes of transport rather than vehicles Reduced greenhouse gas emissions	Positive impact
Noise	Pre-construction and construction	Pre-construction and construction work noise	Minor
		Noise during operating hours of LRT	Minor
	Operation	Reduced noise from road vehicles	Positive impact
Vibration	Pre-construction	Not addressed	
	Construction		
	Operation	Vibration during operating hours	Minor
Visual and functional intrusion /land-use change and aesthetic damage	Pre-construction	Not addressed	
	Construction		
	Operation		
Biodiversity and nature conservation	Pre-construction	NA	
	Construction		
	Operation		
Archaeological and cultural heritage	Pre-construction	NA	
	Construction		
	Operation		
Public utilities and traffic		Transfer of construction equipment leads to possibility of accidents	
	Pre-construction and construction	Interference between project construction movement trucks and other project trucks	Moderate/minor
	Operation	More traffic flow due to higher commercial activities	Minor
Urban development /loss of land and property	Pre-construction	NA	
	Construction		
	Operation		
Involuntary resettlement and vulnerable groups	Pre-construction	NA	
	Construction		
	Operation		
Socio-economic effects	Pre-construction and construction	Offering job opportunities and enhancing incomes	Positive impact
		Unskilled workers' involvement in construction process	
	Operation	High mobility of workers leads to encouraging investment in administrative capital	Positive impact
		Reduced traffic loads Offers job opportunities Reduced number of accidents	

Labor standards and occupational health and safety	Pre-construction Construction	Risk on construction site due to slips, falls and inadequate precautions	Moderate
	Operation	Air pollution, noise, heat and humidity subjection at workplace	Moderate/minor
Community health and safety	Pre-construction Construction	Not addressed	
	Operation	Communities may be impacted by noise, dust, fire, accidents	Minor
Nile and canal instability		NA	

Table A10. Mitigation measures in the pre-construction and construction phase (10th of Ramadan LRT), developed by the authors based on [46].

Project Phase	Environmental/Social Receptor	Proposed Mitigation Measures	Responsible Party	Monitoring/Follow-Up	Significance (After Mitigation)
Pre-Construction and Construction	Soil	Develop soil handling & spill management plan; store & dispose of waste properly; monitor vibration and conduct building surveys; special storage for products	Contractor (supervised by NAT)	-	Negligible
	Waste & Hazardous Waste		Not addressed		
	Water Environment		NA		
	Air Quality & Dust	Machinery dust control, non-deposition of particulate materials, material transport vehicles, washing, clear disposal of excavated materials	Contractor supervised by NAT	Health, Safety, and Environment (HSE) department (environment unit)	Minor
	Noise & Vibration	Pneumatic impact tools, dampen noisy equipment, noise separators, scheduling of truck work, noise barriers and rerouting of trucks	Contractor & NAT	HSE department (environment unit)	Negligible
	Public Utilities & Traffic	Speed limits for trucks and machinery; low traffic time transportation of materials	Contractor & NAT	-	Minor
	Biodiversity / Visual Intrusion		NA		
	Cultural Heritage		NA		
	Socio-Economic		Positive impact		
	OHS (Labor Standards)	Applying safety standards, protective equipment, proper storage of materials, labeling of materials, isolating flammable materials, fire extinguishers	Contractor & NAT	HSE department (industrial safety unit) Healthcare facility	Minor

Land Acquisition and Re-settlement

Not addressed

Table A11. Mitigation measures in the operation phase (10th of Ramadan LRT), based on [46].

Project Phase	Receptor	Mitigation Measures	Responsible Party	Monitoring/Follow-Up	Significance (After-Mitigation)
Operation	Soil	Develop spill management procedures; monitor vibrations and build stability along alignments	Train operating company)	-	Negligible
	Waste Management and air quality	Implement operational Waste Management Plan; ensure segregation, recycling, and proper disposal Ensure proper discharge, emergency procedures dust control and house-keeping	Train operating company	HSE (environmental unit)	Negligible
	Water Environment		NA		
	Noise & Vibration	Proper engineering design & vibration absorption materials	Train operating company	HSE (environmental unit)	Negligible
	Visual / Urban Aesthetics		Not addressed		
	Socio-Economic		Positive		
	OHS & Community Health	Firefighting plan; conduct maintenance of equipment and emergency drills; update health and safety procedures	Train operating company	HSE department (industrial safety unit) Healthcare facility	Negligible

*Appendix A.4. Comparing the Three Case Study Projects***Table A12.** A comparative analysis of the case studies and their impact significance before and after applying mitigation measures.

Project Phase	Receptor	Cairo Metro Line 3 [45]			Cairo Metro Line 4 (NAT, 2010)			10th of Ramadan LRT [46]		
		Before	Mitigation Code(s)	After	Before	Mitigation Code(s)	After	Before	Mitigation Code(s)	After
Pre-Construction	Soil	Minor	M1–M3	Negligible	Minor	M1–M4	Negligible	Moderate	M1–M4	Negligible
	Waste & Hazardous Waste	Negligible	M5–M6	Negligible	Negligible	M5–M6	Negligible	—	—	—
	Water Environment	Minor	M7	Negligible	Minor	M7	Negligible	—	—	—
	Air Quality & Dust	Major	M8–M9	Minor	Major	M8–M9	Minor	Moderate	M33–M40	Minor
	Noise & Vibration	Major	M10–M11	Minor	Major	M10–M11	Minor	Minor	M41–M51	Negligible
	Public Utilities & Traffic	Major	M12	Minor	Major	M12–M13	Minor	Moderate	M52–M57	Minor

	Biodiversity / Visual Intrusion	Major	M14	Negligible	Major	M14	Negligible	—	—	—
	Cultural Heritage	Major	M15–M16	Minor	Major	M15–M16	Minor	—	—	—
	Socio-Economic	Positive impact	M17	Positive	Positive impact	M17	Positive	Positive impact	M17	Positive
	OHS & Labor Standards	Major	M18–M19	Minor	Major	M18–M19	Minor	Moderate	M72–M75	Minor
	Land Acquisition & Resettlement	—	M20–M22	Minor	—	M20–M22	Minor	—	—	—
Construction	Soil	Minor	M23–M25	Negligible	Minor	M23–M25	Negligible	Minor	M24–M25	Negligible
	Waste & Hazardous Waste	Major	M26–M28	Minor	Major	M26–M28	Minor	—	—	—
	Water Environment	Minor	M29–M32	Negligible	Minor	M29–M32	Negligible	Minor	M29–M32	Negligible
	Air Quality & Dust	Major	M33–M36	Minor	Major	M33–M36	Minor	Moderate	M37–M40	Minor
	Noise & Vibration	Major	M41–M45	Minor	Major	M41–M46	Minor	Moderate	M47–M51	Negligible
	Public Utilities & Traffic	Major	M52–M53	Minor	Major	M52–M57	Minor	Moderate	M54–M57	Minor
	Visual & Urban Intrusion	Major	M58	Minor	Major	M58	Minor	—	—	—
	Biodiversity	Minor	M58	Negligible	Minor	M58	Negligible	—	—	—
	Cultural Heritage	Major	M59–M61	Minor	Major	M59–M61	Minor	Moderate	M59–M61	Minor
	Socio-Economic	Positive	M62–M66	Positive impact	Positive	M62–M66	Positive impact	Positive	M62–M66	Positive impact
	OHS & Community Health	Major	M67–M71	Minor	Major	M67–M71	Minor	Moderate	M72–M75	Minor
	Nile & Canal Instability	—	M76–M77	Minor	—	M76–M77	Minor	—	—	—
	Structural Integrity	—	M78–M79	Minor	—	M78–M79	Minor	Moderate	M99–M100	Minor
Operation	Soil	Minor	M80–M81	Negligible	Minor	M80–M81	Negligible	Minor	M80–M81	Negligible
	Waste Management & Air Quality	Minor	M82–M84	Negligible	Minor	M82–M84	Negligible	Minor	M82–M84	Negligible
	Water Environment	Minor	M85–M87	Negligible	Minor	M85–M87	Negligible	—	—	—
	Noise & Vibration	Moderate	M88–M89	Low	Moderate	M88–M89	Low	Minor	M90–M91	Negligible
	Socio-Economic	Positive impact	M92–M94	Positive impact	Positive impact	M92–M94	Positive impact	Positive impact	M92–M94	Positive impact

OHS & Community Health	Moderate	M95–M97	Minor	Moderate	M95–M97	Minor	Moderate	M98	Negligible
Structural Integrity	—	M99–M100	Minor	—	M99–M100	Minor	Moderate	M99–M100	Minor

Appendix A.5. Coding the Mitigation Measures

Table A13. Coding the mitigation measures.

Project Phase	Receptor	Mitigation Measure	Mitigation Code
Pre-Construction	Soil	Develop soil handling & spill management plan.	M1
		Store and dispose of waste properly.	M2
		Monitor vibration and conduct building surveys.	M3
		Special storage for products.	M4
	Waste & Hazardous Waste	Agree on land-fill/dumping sites.	M5
		Prepare Waste Management Plan.	M6
	Water Environment	Maintenance plan for construction machinery.	M7
	Air Quality & Dust	Develop Dust Management Plan.	M8
		Install ambient air quality monitoring.	M9
	Noise & Vibration	Baseline survey for noise and vibration.	M10
		Implement noise/vibration monitoring program.	M11
	Public Utilities & Traffic	Develop detailed utility and traffic deviation plans.	M12
		Keep utilities working in good condition by supporting temporary or permanent diversions.	M13
	Biodiversity / Visual Intrusion	Re-vegetation and urban facility plans agreed before work.	M14
	Cultural Heritage	Conduct additional risk studies.	M15
		Implement chance-find procedure.	M16

Construction	Socio-Economic	Encourage use of local labor.	M17
	Occupational Health, Safety & Labor Standards	Develop OHS Policy and Emergency Response Plan.	M18
		Conduct staff training.	M19
	Land Acquisition and Resettlement	Apply compensation.	M20
		Apply resettlements.	M21
		PAP consultation.	M22
	Soil	Develop and implement Waste Management Plan.	M23
		Apply spill control and soil management procedures.	M24
		Monitor vibration and building stability along alignments.	M25
	Waste & Hazardous Waste	Maintain Waste Registers.	M26
		Coordinate with Cleansing Authorities.	M27
		Ensure proper storage, transport, recycling, and licensed disposal.	M28
	Water Environment	Apply strict spill prevention.	M29
		Protect water-courses.	M30
		Prevent illegal dumping.	M31
		Monitor groundwater and drainage quality.	M32
	Air Quality & Dust	Implement Dust Management Plan.	M33
		Use low-emission (EURO V) machinery.	M34
		Apply diesel particulate filters.	M35
		Conduct air quality monitoring.	M36
		Machinery dust control.	M37

	Non-deposition of particulate materials.	M38
	Transporting materials vehicles.	M39
	Washing and clear disposal of excavated materials.	M40
Noise & Vibration	Schedule noisy work for daytime.	M41
	Install temporary noise barriers.	M42
	Continuous noise and vibration monitoring.	M43
	Conduct noise impact study.	M44
	Install permanent barriers if required.	M45
	Use special equipment and scheduling for truck work.	M46
	Pneumatic impact tools.	M47
	Dampen noisy equipment.	M48
	Noise separators.	M49
	Schedule truck work.	M50
	Noise barriers and rerouting of trucks.	M51
Public Utilities & Traffic	Prepare and implement Traffic Management Plan.	M52
	Coordinate with relevant authorities for diversions and restoration.	M53
	Temporary steel structures as a substitute for vehicle movement.	M54
	Manage alternative routes.	M55
	Speed limits to trucks and machinery.	M56
	Low traffic time transportation of materials.	M57
Biodiversity / Visual Intrusion	Replant trees and restore vegetation	M58

Cultural Heritage	immediately after completion.	
	Conduct detailed archaeological study.	M59
	Ensure archaeologist present during excavation.	M60
	Non-destroying surveying.	M61
Socio-Economic	Hire local labor.	M62
	Maintain access routes.	M63
	Coordinate with affected businesses.	M64
	Communicate construction schedules.	M65
	Prioritize local labor, apply pedestrian crossings, plan for services and activities, and provide training for workers.	M66
Occupational Health, Safety & Community Health	Enforce OHS standards—International Labour Organization-compliant	M67
	Provide PPE, training, and Emergency Response Plan.	M68
	Engage communities.	M69
	Provide fire extinguishers and correct storage for flammable materials.	M70
	Adhere to public health and safety standards.	M71
	Apply safety standards and provide protective equipment.	M72
	Proper storage and labeling of materials.	M73
	Isolate flammable materials.	M74
	Provide fire extinguishers.	M75
Nile and Canal Instability	Conduct geotechnical surveys.	M76

Operation	Structural Integrity	Work in coordination with the Nile Research Institute.	M77
		Apply risk categorization zones.	M78
		Conduct settlement numerical analysis.	M79
	Soil	Develop spill management procedures.	M80
		Monitor vibrations and building stability along alignments.	M81
	Waste Management & Air Quality	Implement operational Waste Management Plan.	M82
		Ensure segregation, recycling, and proper disposal.	M83
		Ensure proper discharge, emergency procedures, dust control, and house-keeping.	M84
	Water Environment	Maintain drainage systems.	M85
		Monitor groundwater and wastewater.	M86
		Enforce spill prevention protocols.	M87
	Noise & Vibration	Regular maintenance of rails, wheels, and rolling stock.	M88
		Periodic noise/vibration monitoring at sensitive receptors.	M89
		Proper engineering design and vibration absorption materials.	M90
		Apply vibration absorption equipment and proper engineering design.	M91
	Socio-Economic	Maintain reliable service.	M92
		Uphold safety and accessibility.	M93
		Ensure effective public	M94

	communication and grievance redress.	
Occupational & Community Health and Safety	Implement Emergency Response Plan.	M95
	Conduct staff safety training and emergency drills.	M96
	Update health and safety procedures. Firefighting plan; conduct maintenance of equipment and emergency drills; update health and safety procedures.	M97
		M98
Structural Integrity	Apply vibration absorption equipment and proper engineering design.	M99
	Conduct maintenance and vibration monitoring.	M100

Appendix A.6. Framework Interface

Interface

The screenshot displays the EIA Risk & Mitigation Management software interface. The top section, titled 'Interface', shows the 'Project List' with columns for Project Name, Location, Scope, Status, Start Date, and End Date. Below this, the 'Risk module' is shown, featuring a table with columns for Risk ID, Related project name, Risk Description, A.L., R.L., Project, Severity, Risk Priority, Mitigation Measures, and Risk Category After. The table lists various risks associated with the Cairo Monorail Project, categorized by severity (Major, Moderate, Minor) and risk priority (High, Medium, Low). The interface includes navigation tabs for Mitigation Measures, Projects, and Add or import, as well as a sidebar with options like Grid view and Find a view.

Figure A1. The proposed framework interface and risk module (red: high risk, yellow: moderate risk, light green: low risk, dark green: positive impact).

EIA Risk & Mitigation Management Data Automations Interfaces Forms Trial: 3 days left Launch Share

Risks Mitigation Measures Projects Add or import

Grid view Hide fields Filter Group IT Sort Color Share and sync

	A Mitigation Code	A Mitigation Measure...	Description	Estimate...	project phase	Linked Risk	Related Project (from Ri...	Implementation...	Receptor...
1	M1	Develop soil handling & sp...	Pre-Construction - Soil De...	\$10.00	pre construction	RISK-101 RISK-ML4-001	Metro line 3 phase 3	11/24/2025	Soil, Soil, Soil
2	M2	Store and dispose of waste...	Pre-Construction - Soil: Sto...		pre construction	RISK-LRT-027		11/25/2025	Soil
3	M3	Monitor vibration and con...	Pre-Construction - Soil: Mo...	\$20.00	pre construction	RISK-101	Metro line 3 phase 3	11/29/2025	Soil
4	M4	Special storage for products.	Pre-Construction - Soil: Sp...		pre construction	RISK-ML4-001 RISK-LRT-02		11/25/2025	Soil, Soil
5	M5	Agree on landfill/dumping ...	Pre-Construction - Waste ...		pre construction	RISK-106	Metro line 3 phase 3	11/16/2025	waste and hazar.
6	M6	Prepare Waste Manage...	Pre-Construction - Waste ...		pre construction	RISK-106	Metro line 3 phase 3		waste and hazar.
7	M7	Maintenance plan for const...	Pre-Construction - Water E...		pre construction	RISK-109 RISK-ML4-005	Metro line 3 phase 3		water environme
8	M8	Develop Dust Management...	Pre-Construction - Air Qual...		pre construction	RISK-113 RISK-114 RISK-	Metro line 3 phase 3, Metro lin...		dust and air qual
9	M9	Install ambient air quality ...	Pre-Construction - Air Qual...		pre construction	RISK-113 RISK-114 RISK-	Metro line 3 phase 3, Metro lin...		dust and air qual
10	M10	Baseline survey for noise a...	Pre-Construction - Noise &...		pre construction	RISK-118 RISK-121 RISK-	Metro line 3 phase 3, Metro lin...		noise, vibration, .
11	M11	Implement noise/vibration ...	Pre-Construction - Noise &...		pre construction	RISK-118 RISK-121 RISK-	Metro line 3 phase 3, Metro lin...		noise, vibration, .
12	M12	Develop detailed utility an...	Pre-Construction - Public U...		pre construction	RISK-140 RISK-ML4-028	Metro line 3 phase 3		public utilities a.
13	M13	Keep utilities working in go...	Pre-Construction - Public U...		pre construction	RISK-ML4-028			Public utilities a.
14	M14	Re-vegetation and urban fa...	Pre-Construction - Biodiver...		pre construction	RISK-126 RISK-127 RISK-	Metro line 3 phase 3, Metro lin...		Visual and functi.
15	M15	Conduct additional risk stu...	Pre-Construction - Cultural...		pre construction	RISK-137 RISK-ML4-035	Metro line 3 phase 3		archaeological a.
16	M16	Implement chance-find pro...	Pre-Construction - Cultural...		pre construction	RISK-137 RISK-ML4-035	Metro line 3 phase 3		archaeological a.
17	M17	Encourage use of local labor.	Pre-Construction - Socio-E...		pre construction	RISK-148 RISK-149	Metro line 3 phase 3, Metro lin...		socio-economic .
18	M18	Develop OHS Policy and E...	Pre-Construction - Occupat...		pre construction	RISK-153 RISK-ML4-027	Metro line 3 phase 3		occupational he.
19	M19	Conduct staff training.	Pre-Construction - Occupat...		pre construction	RISK-153 RISK-ML4-027	Metro line 3 phase 3		occupational he.
20	M20	Apply compensation.	Pre-Construction - Land Ac...		pre construction	RISK-146 RISK-147 RISK-	Metro line 3 phase 3, Metro lin...		vulnerable grou.
21	M21	Apply resettlements.	Pre-Construction - Land Ac...		pre construction	RISK-ML4-029 RISK-ML4-03			Urban Develop...
		PAPs consultation.	Pre-Construction - Land Ac...		pre construction	RISK-146 RISK-147 RISK-	Metro line 3 phase 3, Metro lin...		vulnerable grou.

173 records Sum \$30.00

Figure A2. The proposed framework mitigation measures module.

EIA Risk & Mitigation Management Data Automations Interfaces Forms Trial: 3 days left Launch Share

Risks Mitigation Measures Projects Add or import

Grid view Hide fields Filter Grouped by 1 field IT Sort Color Share and sync

	A receptor name	Receptor Typ...	Project...	Severity	R	Mitigation Measures	Risk Category After...	Number o
34	Visual and functional in...	environmental	Pre-Construct...	Major	1.0	M14	negligible	
	Biodiversity and nature ...	social	Pre-Construct...	Major	1.0	M14	negligible	
36	Archaeological and cult...	social	Pre-Construct...	Major	1.0	M15 M16	negligible	
37	Public utilities and Traffic	social	Pre-Construct...	Major	1.0	M12 M13	minor	
38	Urban Development /lo...	social	Pre-Construct...	Major	1.0	M20 M21 M22	minor	
39	Labour standards and o...	social	Pre-Construct...	Major	1.0	M18 M19	minor	
40	Community health and ...	social	Pre-Construct...	Major	1.0	M18 M19	minor	
41	Nile and canal instabity	environmental	Pre-Construct...	Major	1.0	M76 M77	minor	
42	Soil	environmental	Pre-Construct...	Moderate	1.0	M2 M1 M4	negligible	
43	Dust and air quality	environmental	Pre-Construct...	Moderate	1.0	M33 M34 M35 M36	minor	
44	Noise	environmental	Pre-Construct...	Minor	2.0	M41 M42 M43 M44	negligible	
45	Public utilities and Traffic	social	Pre-Construct...	Moderate	1.0	M52 M53 M54 M55	minor	
46	National Economy/Cont...	social	Pre-Construct...	Major	1.0	M99	minor	
47	Social Fabric/Landowners	social	Pre-Construct...	Major	1.0	M100	minor	
48	Labour standards and o...	social	Pre-Construct...	Moderate	1.0	M72 M73 M74 M75	minor	
49	Community health and ...	social	Pre-Construct...	Moderate	1.0	M72 M73 M74 M75	minor	
50	Technical Design	environmental	Pre-Construct...	Moderate	1.0	M106 M124	minor	
51	Socio-economic effect	social	Pre-Construct...	Positive impact	0.0	M107 M113 M127	positive	
52	Finance/Cost Risk	social	Pre-Construct...	Major	1.0	M108 M132	negligible	
53	Technical/Design	social	Pre-Construct...	Major	1.0	M110 M134	minor	
	economic effect	social	Pre-Construct...	Major	1.0	M125 M129	negligible	

51 cells selected

Figure A3. The proposed framework receptor module red: high risk, yellow: moderate risk, light green: low risk, dark green: positive impact).

Risk ID	Related project name	Risk Description	Receptor name	Receptor Type	Project	Severity	Mitigation Measures	Risk Category
PROJECT PHASE Pre-Construction 31						Sum 59.0		
PROJECT PHASE Construction						Sum 69.0		
PROJECT PHASE Operation 40						Sum 52.0		
123 RISK-105	Metro line 3 phase 3	Soil disturbance due to leakage/vibration	Soil	environmental	Operation	Minor	2.0 M80 M81	negligible
124 RISK-108	Metro line 3 phase 3	Generated operation waste	waste and hazardous w...	environmental	Operation	Minor	2.0 M82 M83 M84	negligible
125 RISK-112	Metro line 3 phase 3	Ground water contamination due to in...	water environment	environmental	Operation	Minor	2.0 M85 M86 M87	negligible
126 RISK-117	Metro line 3 phase 3	Reduction of bad emissions due to usin...	dust and air quality	environmental	Operation	Major	1.0 M82 M83 M84	negligible
127 RISK-120	Metro line 3 phase 3	Noise during operating hours of metro	noise	environmental	Operation	Major	1.0 M89	negligible
128 RISK-125	Metro line 3 phase 3	Vibration during operating hours	vibration	environmental	Operation	Minor	2.0 M88 M89	negligible
129 RISK-133	Metro line 3 phase 3	Poor Commitment to regreening and f...	Visual and functional in...	environmental	Operation	Major	1.0 M58	minor
130 RISK-142	Metro line 3 phase 3	Reduction of reliance on other means o...	public utilities and traffic	social	Operation	Minor	2.0 M52 M53	minor
131 RISK-144	Metro line 3 phase 3	Engraving agricultural land for urban u...	urban development	social	Operation	Minor	2.0 M58	negligible
132 RISK-145	Metro line 3 phase 3	Community character changes	urban development	social	Operation	Minor	2.0 M58	negligible
133 RISK-152	Metro line 3 phase 3	High mobility of workers leads to enha...	socio-economic effect	social	Operation	Positive impact	0.0 M62 M63 M64 M65	positive
134 RISK-155	Metro line 3 phase 3	Risks resulted from poor implementati...	occupational health an...	social	Operation	Major	1.0 M67 M68 M69 M70	minor
135 RISK-156	Metro line 3 phase 3	Communities surrounding the project l...	community health and ...	social	Operation	Major	1.0 M62 M63 M64 M65	minor
136 RISK-ML4-004	metro line 4 phase 1	Pollution due to oil leakage and waste...	Soil	environmental	Operation	Minor	2.0 M80 M81	negligible
137 RISK-ML4-006	metro line 4 phase 1	Ground water Pollution due to oil leaka...	Water environment	environmental	Operation	Minor	2.0 M85 M86 M87	negligible
+ Add... 4-009	metro line 4 phase 1	Secondary impact resulted from emissi...	Dust and air quality	environmental	Operation	Minor	2.0 M82 M83 M84	negligible

Figure A4. The proposed framework project lifecycle module red: high risk, yellow: moderate risk, light green: low risk, dark green: positive impact).

Risk ID	Related project name	Risk Description	Receptor name	Receptor Type	Project	Severity	Mitigation Measures	Risk Category
SEVERITY Negligible 2						Sum 6.0		
SEVERITY Minor 39						Sum 78.0		
SEVERITY Moderate 33						Sum 33.0		
SEVERITY Major						Sum 63.0		
SEVERITY Positive impact 13						Sum 0.0		
150 RISK-148	Metro line 3 phase 3	Offering job opportunities and enhanci...	socio-economic effect	social	Pre-Construct...	Positive impact	0.0 M17	positive
151 RISK-149	Metro line 3 phase 3	Unskilled workers' involvement in const...	socio-economic effect	social	Pre-Construct...	Positive impact	0.0 M17	positive
152 RISK-150	Metro line 3 phase 3	Offering job opportunities and enhanci...	socio-economic effect	social	Construction	Positive impact	0.0 M62 M63	positive
153 RISK-151	Metro line 3 phase 3	Unskilled workers' involvement in const...	socio-economic effect	social	Construction	Positive impact	0.0 M64 M65 M66	positive
154 RISK-152	Metro line 3 phase 3	High mobility of workers leads to enha...	socio-economic effect	social	Operation	Positive impact	0.0 M62 M63 M64 M65	positive
155 RISK-LRT-038	10th of ramdan LRT	Reduction of bad emissions due to usin...	Dust and air quality	environmental	Operation	Positive impact	0.0 M82 M83 M84	negligible
156 RISK-LRT-026	10th of ramdan LRT	Reduced greenhouse gas emissions	Dust and air quality	environmental	Operation	Positive impact	0.0 M82 M83 M84	negligible
157 RISK-LRT-011	10th of ramdan LRT	Unskilled workers' involvement in const...	Socio-economic effects	social	Construction	Positive impact	0.0 M62 M63 M64 M65	positive
158 RISK-LRT-007	10th of ramdan LRT	Reduced traffic loads	Socio-economic effects	social	Operation	Positive impact	0.0 M92 M93 M94	positive
159 RISK-LRT-031	10th of ramdan LRT	Offers job opportunities	Socio-economic effects	social	Operation	Positive impact	0.0 M92 M93 M94	positive
160 RISK-409	Egypt High-Speed Rail (HSR)	Offering high-skilled job opportunities ...	Socio-economic effect	social	Pre-Construct...	Positive impact	0.0 M107 M113 M127	positive
161 RISK-506	Cairo Monorail Project	Increased property value for parcels ne...	Socio-economic effect	social	Operation	Positive impact	0.0 M116	positive
+ Add...	Cairo Metro Line 2 Upgrade	Improved service reliability reducin...	Socio-economic effect	social	Operation	Positive impact	0.0 M127	positive

Figure A5. The proposed framework risk-level module red: high risk, yellow: moderate risk, light green: low risk, dark green: positive impact).

Project Name	Project Type	Location	Scope	Status	Risks	Duration (Days)
1 Metro line 3 phase 3	Infrastructure	Cairo, Egypt	Connects Attaba → Rod El ...	Completed	RISK-101 RISK-117 RISK-...	M1 M3
2 metro line 4 phase 1	Infrastructure	Cairo, Egypt	connects El Malek El Saleh ...	Completed	RISK-ML4-001 RISK-ML4-0...	M1 M4
3 10th of ramdan LRT	Infrastructure	Cairo, Egypt	connects from Adly Manso...	Construction	RISK-LRT-027 RISK-LRT-002	M2 M1
4 Egypt High-Speed Rail (HS...	Infrastructure	Red Sea, Egypt	Connects Ain Sokhna → M...	Construction	RISK-401 RISK-404 RISK-...	M99 M
5 Cairo Metro Line 2 Upgrade	Infrastructure	Cairo, Egypt	Connecting Shoubra El Kh...	Construction	RISK-601 RISK-602 RISK-...	M123 M
6 Cairo Monorail Project	Infrastructure	Cairo, Egypt	NAC Line: Connects Stadi...	Construction	RISK-501 RISK-503 RISK-...	M111 f

Figure A6. The ESIA report data module.

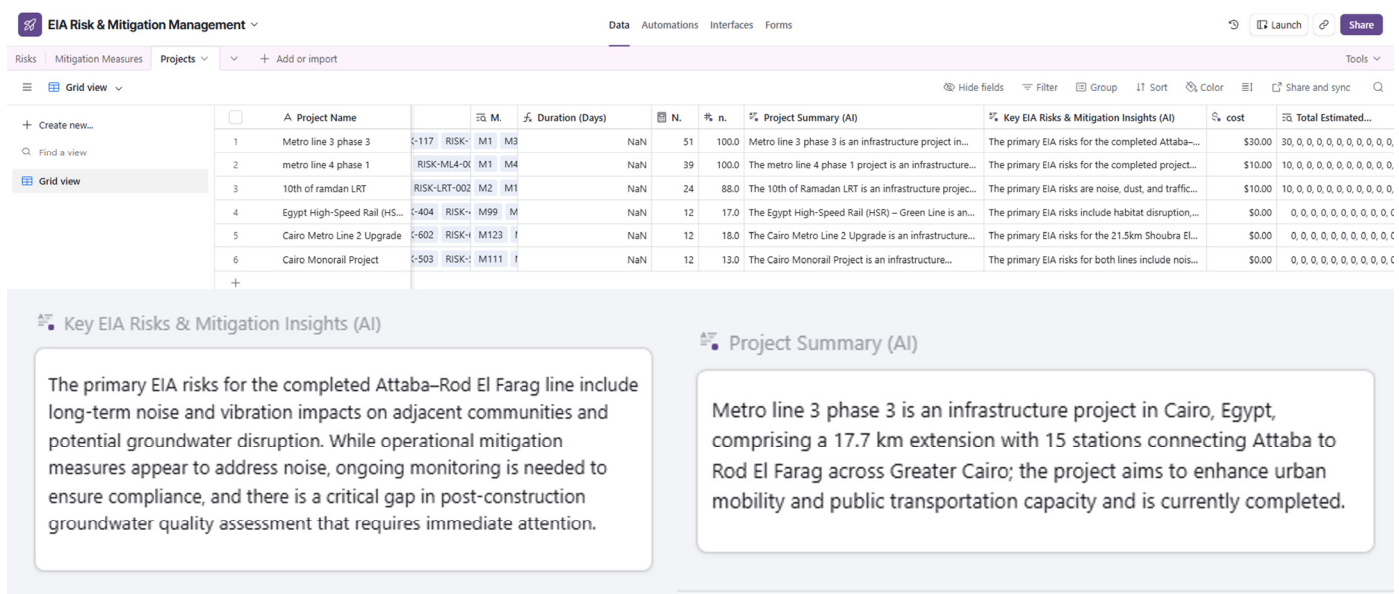


Figure A7. The automation module.

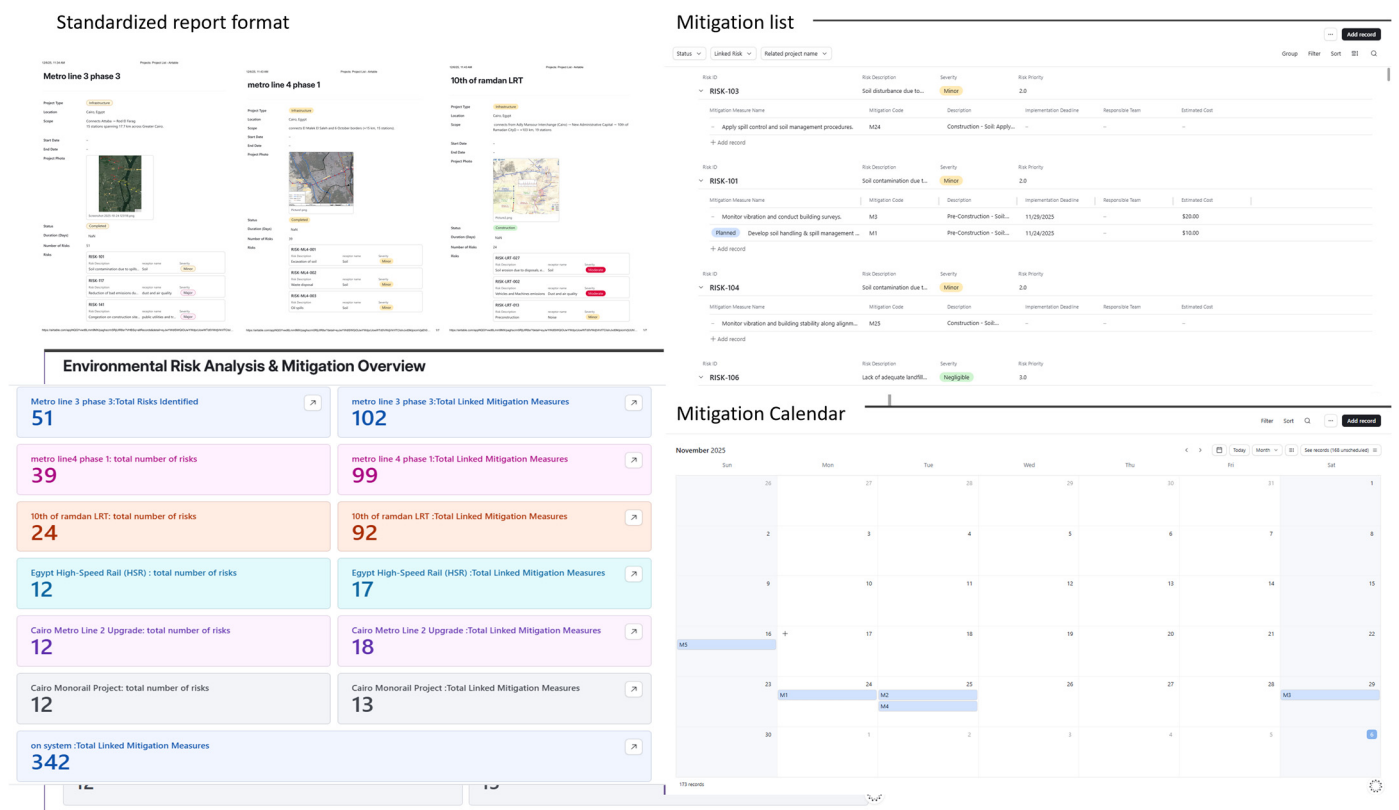


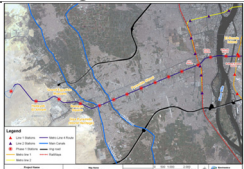
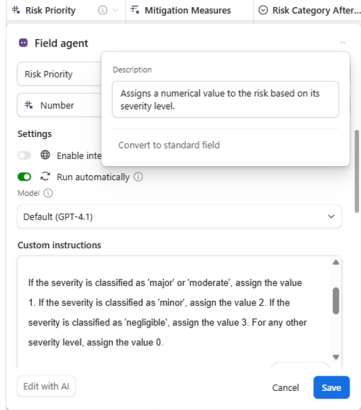
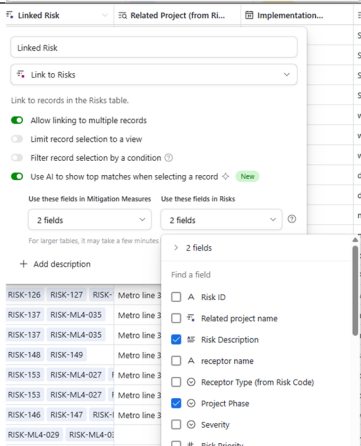
Figure A8. Output framework 1 showing the standardized report format for the three case studies, comparing their risks and mitigation measures and proposing a management calendar.



Figure A9. Output model 2 comparing risks by severity and category across different project phases for each case study project.

Appendix A.7. Data Input for Cairo Metro Line 3 Phase 3

Table A14. Data input for Cairo Metro Line 3 Phase 3.

Category	Inputs	Example
Project-Level Inputs	Project name	Cairo Metro Line 3 Phase 3
	Project type	Infrastructure, residential, commercial, etc.
	Start and end date	MM/DD/YY
	Current status	In progress, completed, planning, etc.
	Project image	
Risk Inputs	Risk type	Environmental/ social
	Severity before mitigation	Major/ minor/ negligible/ positive
	Associated receptor	Air quality, soil, noise, etc.
	Associated lifecycle phase	Pre-construction, construction, operation
	Risk description	Oil spills during construction phase cause soil pollution
Mitigation Inputs	Mitigation description	Develop spill management plan
	Implementation cost	30\$
	Linked risks	R1, R2, etc.
	Deadline	MM/DD/YY
	Responsible party	Contractor
AI Input Parameters	Severity priority condition rules	
	Lookup references	

Summarization prompts for text generation

The screenshot shows a web interface for generating EIA risk insights. At the top, there are tabs for 'Key EIA Risks & Mitigation Insights (AI)', 'cost', and 'Total Estimate'. Below the tabs, there is a 'Field agent' section with a dropdown menu set to 'Key EIA Risks & Mitigation Insights (AI)' and a 'Long text' dropdown. There are also checkboxes for 'OneDrive' (with a 'New' button) and 'Run automatically'. A 'Model' dropdown is set to 'Default (GPT-4.1)'. A 'Custom instructions' box contains the following text: 'You are an environmental risk analyst with expertise in EIA (Environmental Impact Assessment) for architecture and infrastructure projects. Your role is to provide concise, actionable insights on EIA risks and mitigation measures, highlighting urgent issues or gaps, using a clear and analytical tone.' Below the instructions box is an 'Insert field' button. At the bottom, there are 'Edit with AI', 'Cancel', and 'Save' buttons.

Prompt:

You are an environmental risk analyst with expertise in EIA for architecture and infrastructure projects. Your role is to provide concise, actionable insights on EIA risks and mitigation measures, highlighting urgent issues or gaps, using a clear and analytical tone.

Task description:

Analyze the project's scope and current status to identify the most significant EIA risks and the effectiveness of corresponding mitigation strategies. Highlight any urgent risks, critical gaps in mitigation, or areas requiring immediate attention. Focus on providing practical insights that support project management and regulatory compliance.

Output format:

Write a brief analysis in plain text (2-3 sentences), directly addressing the most important risks and mitigation insights without headings, lists, or extraneous commentary. If insufficient information is available, output "Insufficient data to provide EIA risk and mitigation insights." Example: "The main EIA risks involve groundwater contamination and air quality impacts. Current mitigation measures address these risks, but additional controls may be needed for dust management during construction." (Real examples should be similar in length and detail, tailored to the provided data.)

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